Neutrino Interaction Measurements

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Outline

Quasi-elastic scattering cross section

Coherent pion production

MINERvA

T2K

Last year at PIC 2010, Michael Wilking gave an excellent review of neutrino interactions. I refer you to those proceedings for a good review through mid-2010.

I want to emphasize in this talk some of the most recent results, some very intriguing aspects of them, and near term prospects for new results.

Neutrino Beamlines

The discovery of neutrino oscillations led to the building of intense neutrino beamlines at CERN, KEK, and FNAL in the first decade of the 21st century.

Peak neutrino energies range from below 1 GeV (T2K, BooNE) to 4-10 GeV (CNGS, NuMI).

Although built to study oscillations, these new neutrino sources present a great opportunity to do high statistics neutrino scattering.

The Good, Bad, and Ugly of Neutrino Interactions

Good – Only interacts weakly

Unique probe for nucleon structure due to its flavor sensitivity

Bad – Can't detect scattered neutrino

Cross sections are small

Need massive targets for good statistics

Ugly – Don't know the incident neutrino energy

Need detailed Monte Carlo comparisons to extract most results

Interactions and Oscillations

Oscillation experiments require knowledge of interactions to know to neutrino energy and to estimate background processes.

Oscillations depend on L/E

E is not known, determined from summed visible energy of outgoing particles.

When the interaction is in a nucleus, outgoing final state can result in missed energy (binding energy and neutrons produced through nucleon FSI, pion absorption)

Determination of event rates requires background subtraction

Good estimate of systematic effects require MC to estimate backgrounds. Need both cross sections and final state characteristics (energy spectra, particles emitted)

Intrinsic Interest in Interactions

Nucleon properties

- Nucleon Form Factors (neutrino scattering only practical way to determine axial form factor)
- PDF's (neutrinos give flavor sensitivity, F3)

Nuclear effects

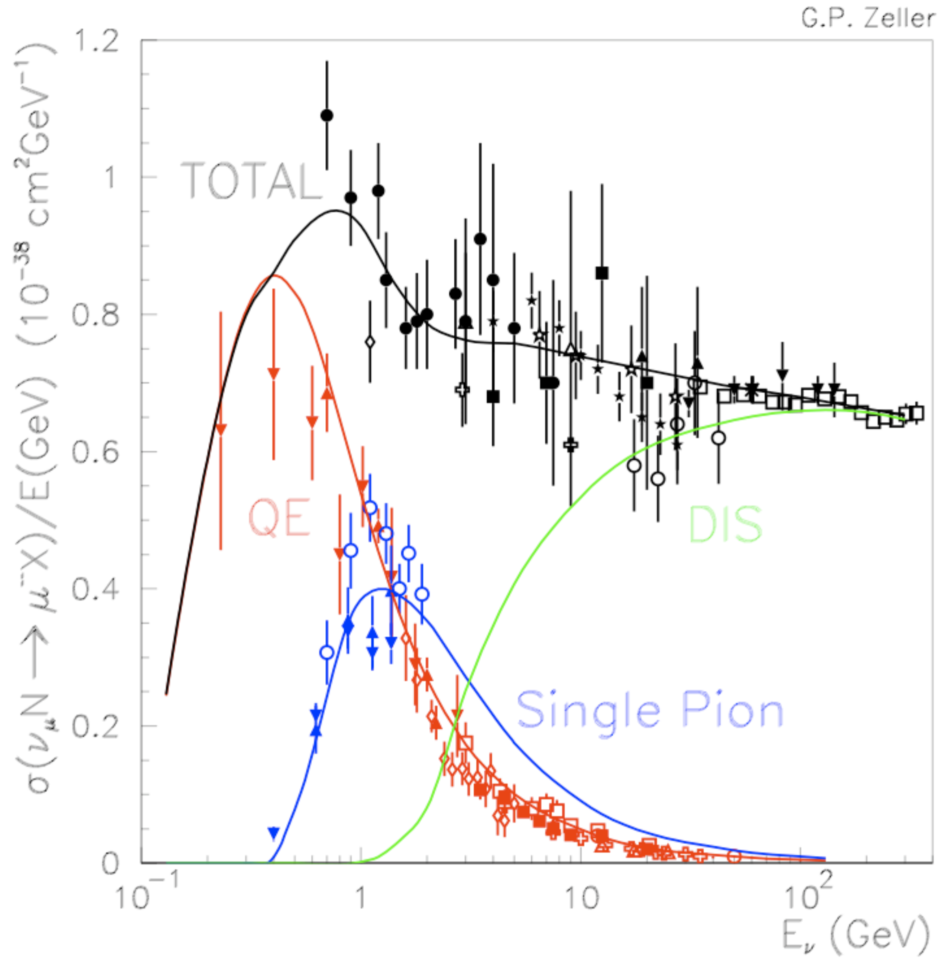
- Medium modification of form factors/PDF
- Coherent pion production
- x-dependent A dependence (e.g. shadowing)

Neutrino Cross Sections

Below 1 GeV quasi-elastic QE ($\nu N \rightarrow \mu N$) dominates

For 1-5 GeV, QE, resonance (single π production) are about equal and multiple π production and DIS begin to contribute

Above 5 GeV, DIS dominates

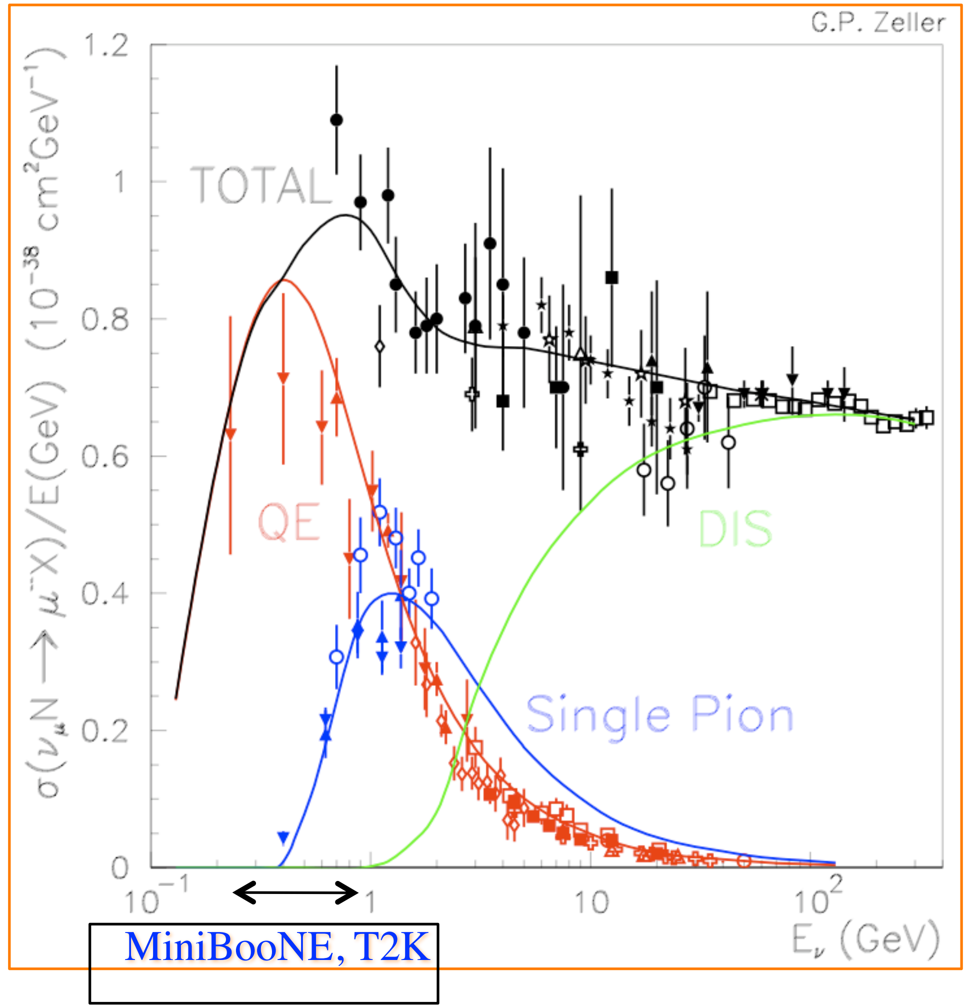


Plot courtesy G.P. Zeller

Neutrino Cross Sections

Recent and current oscillation experiments (MiniBooNE, SciBooNE, T2K) are done below 1 GeV where QE dominates.

Understanding QE is critical to oscillation experiments

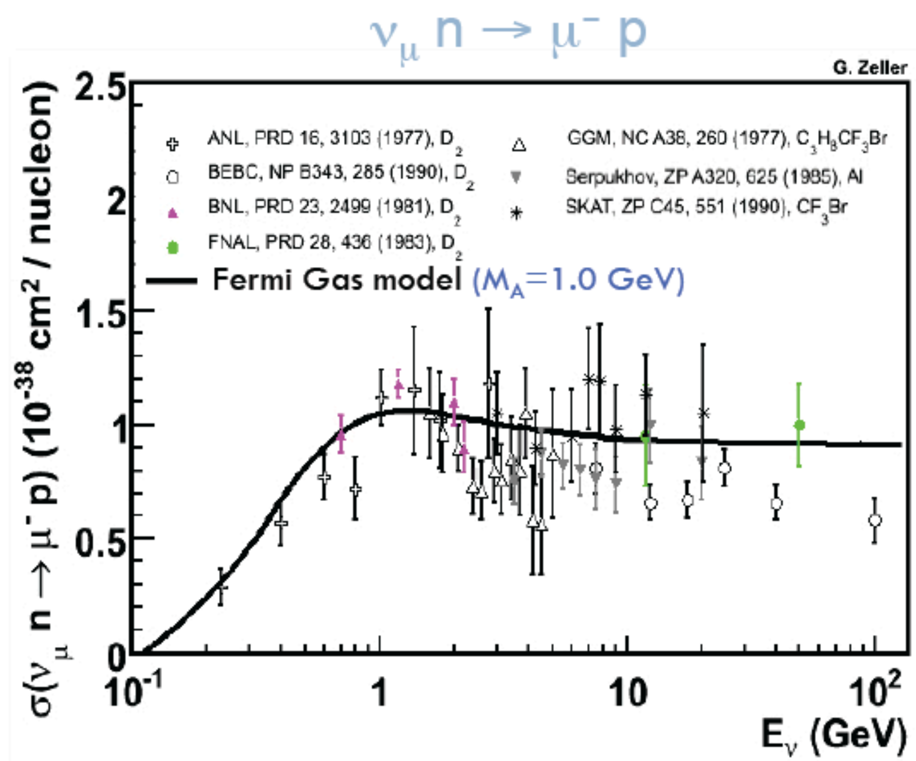


Plot courtesy G.P. Zeller

Quasi-elastic Scattering

Until recently QE was thought to be fairly well understood.

Well described by vector form factors measured with electron scattering, and with dipole form factor for G_A.



Plot courtesy G.P. Zeller

QE and Oscillations

QE plays a special role in oscillation studies.

- Provides best measure of neutrino energy
  - As a 2 body reaction, detection of muon energy and angle alone determines neutrino energy (within smearing due to fermi-motion/binding energy)
- Much of signal for low energy oscillations (e.g. MiniBooNE)

QE Cross-section

Differential cross section is proportional to constants, kinematic factors, and form factors.

$$\frac{d\sigma}{dQ^2} = \frac{M^2 G^2 \cos^2\theta_c}{8\pi E_\nu^2}\left[A(Q^2) - B(Q^2)(s-u) + C(Q^2)(s-u)^2\right]$$

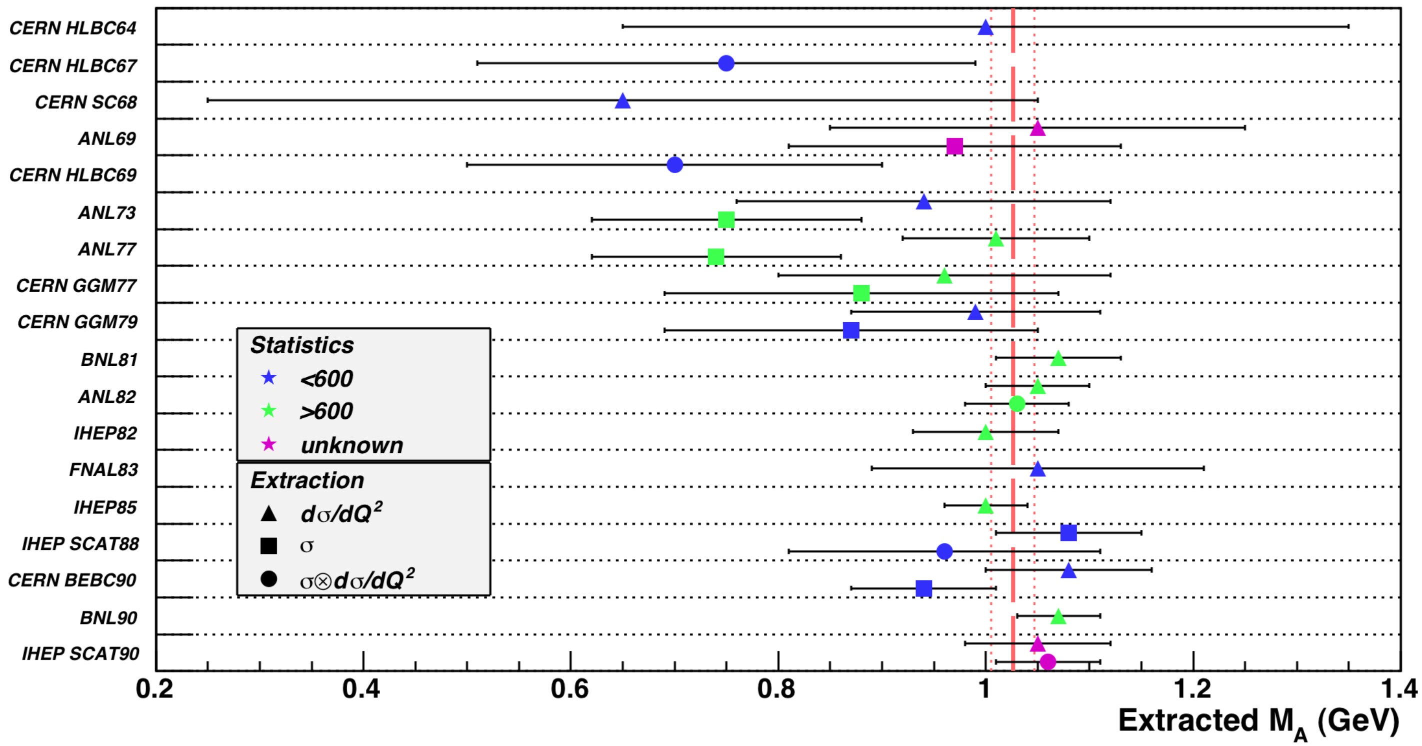
A, B, and C are functions of the vector and axial form factors. The vector form factors G_E and G_M are determined from electron scattering experiments.

$$G_{Ep} = \frac{1}{(1+Q^2/0.71)^2} \qquad G_{Mp,n} = \frac{\mu_{p,n}}{(1+Q^2/0.71)^2} \qquad G_A = \frac{G_A(0)}{(1+Q^2/M_A^2)^2}$$

QE Cross-section

$G_A(0)$ determined from beta decay

M_A "axial mass" determined from QE neutrino scattering in bubble chamber experiments

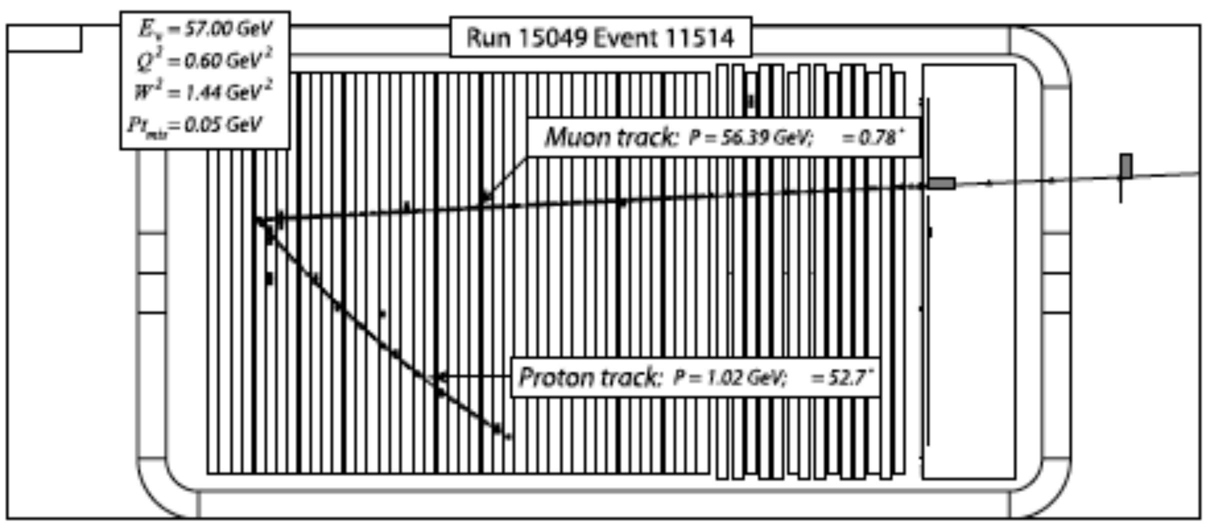


Plot courtesy B. Ziemer

M_A found to be ~1.03 with good agreement between experiments – in 2000 all seemed fine…

NOMAD

NOMAD, an experiment at CERN, used drift chambers to make a high statistics study of QE scattering. Target nucleus was mainly C, with neutrino energy of 5-100 GeV



Lyubushkin et al, EPJ-C **63,** 355 (2009)

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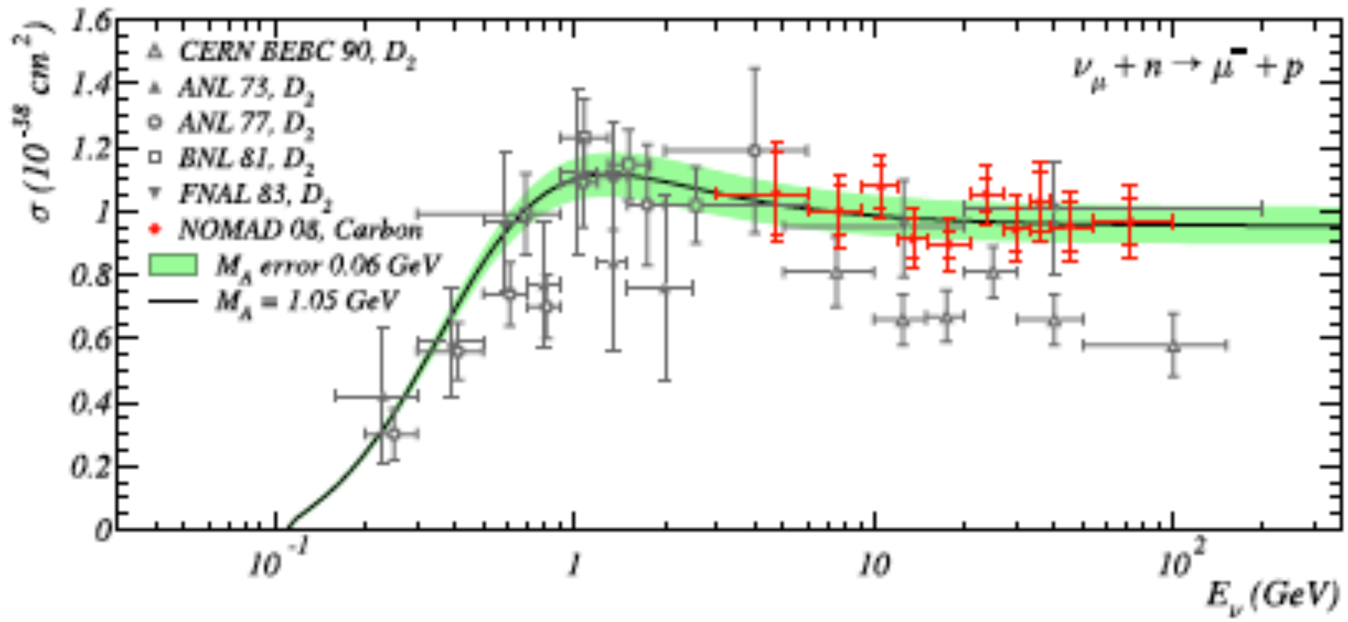
NOMAD

Target nucleus was mainly carbon, but results for M_A ~1.05, was generally consistent with those from bubble chambers



Lyubushkin et al, EPJ-C **63,** 355 (2009)

MiniBooNE and SciBooNE

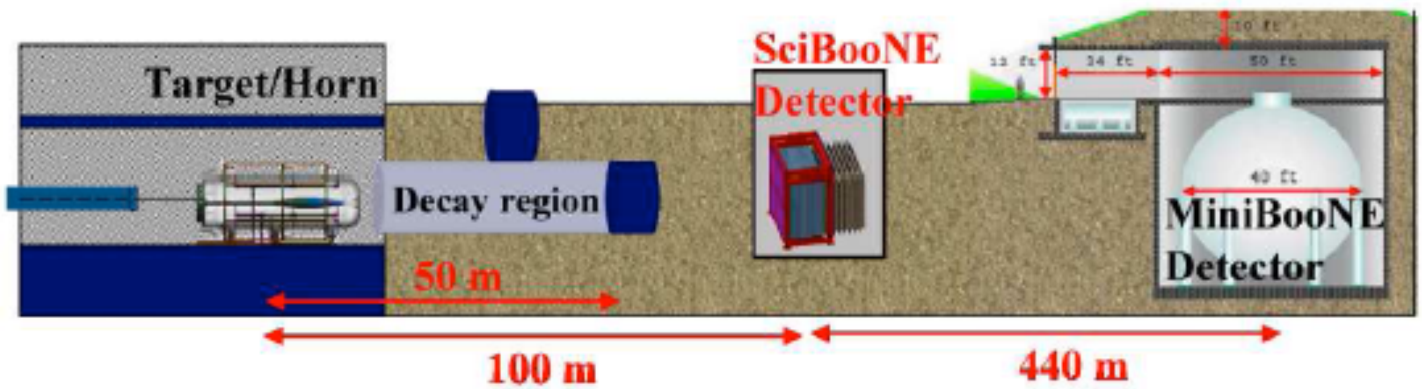
MiniBooNE was designed to test LSND oscillation results. The detector is mineral oil (CH_2) and detects Cerenkov radiation.

SciBooNE consists of plastic scintillator (CH).

For QE with neutrinos, both are C targets.

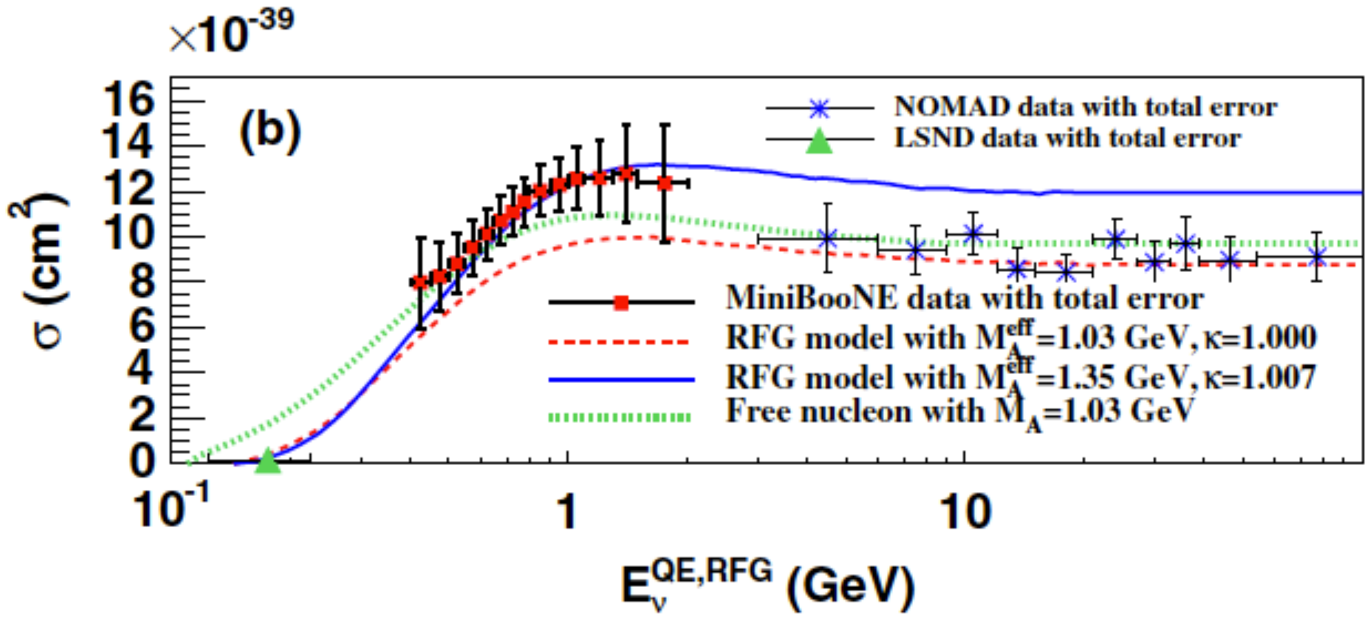
Beam energy range is about 0.5-1 GeV

First non-bubble chamber data < 1 GeV



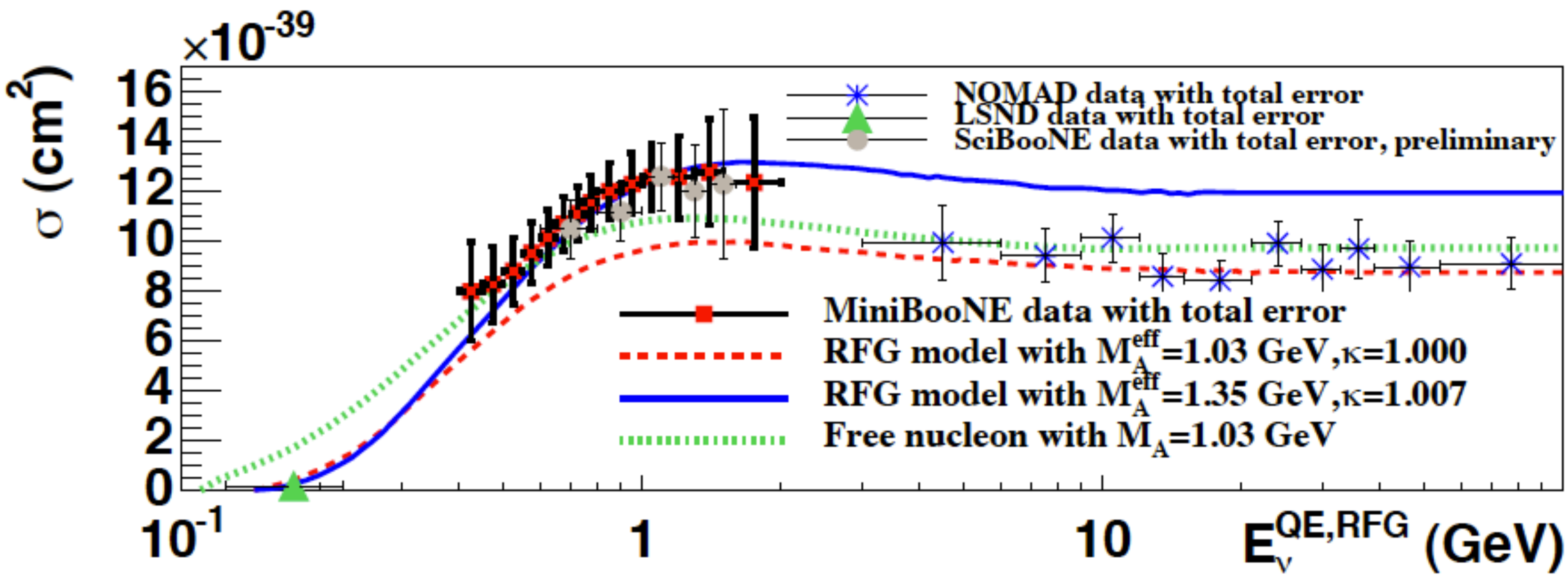
MiniBooNE QE

MiniBooNE did not agree with previous results. Data were higher than expected, and required M_A of about 1.35.

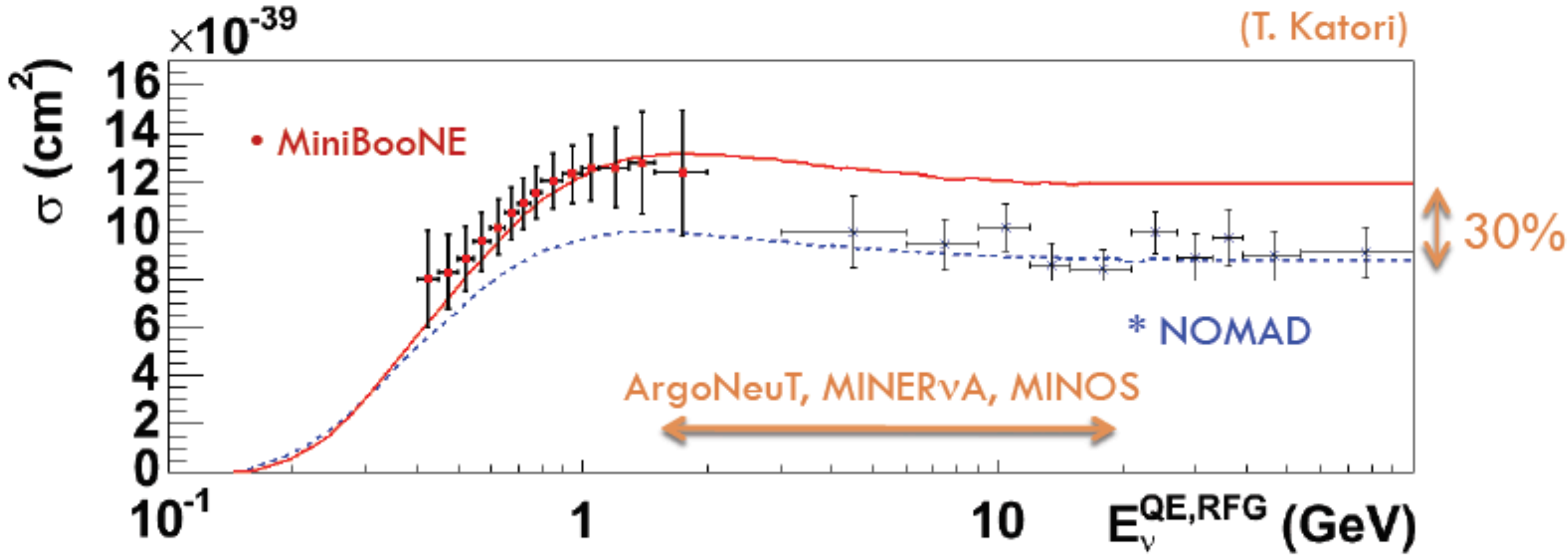


From A.A. Aguilar-Arevalo, PRD **81**, 092005 (2010)

And SciBooNE Agreed with MiniBooNE



Plot from M.O. Wascko, NP-B Suppl. 00, 1 (2011)



Low and high energy data appear inconsistent. The intermediate region is being measured by MINERvA, MINOS, and ArgoNeut.

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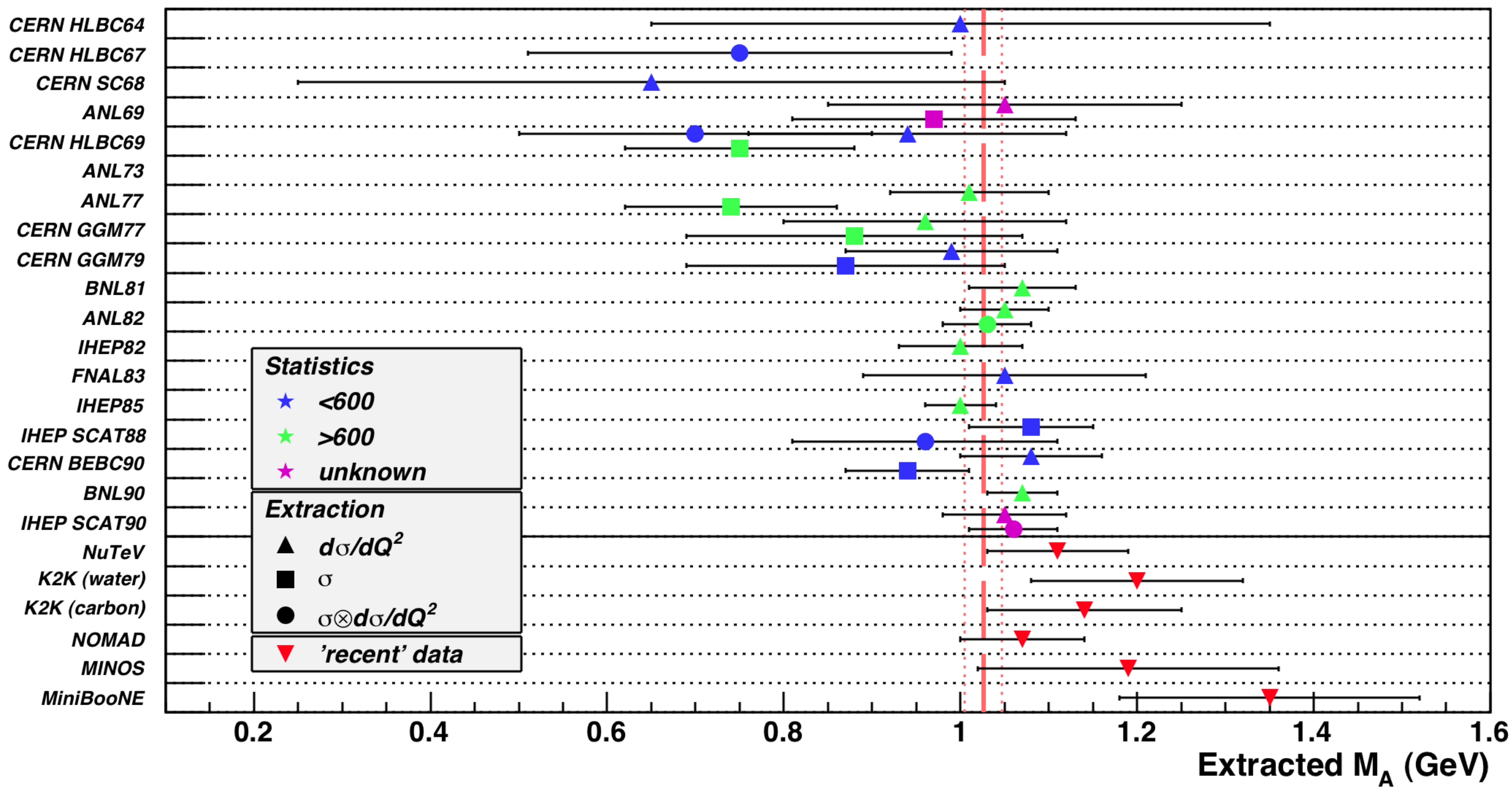
Other low E extractions of M_A from non-bubble chamber data also give higher values.

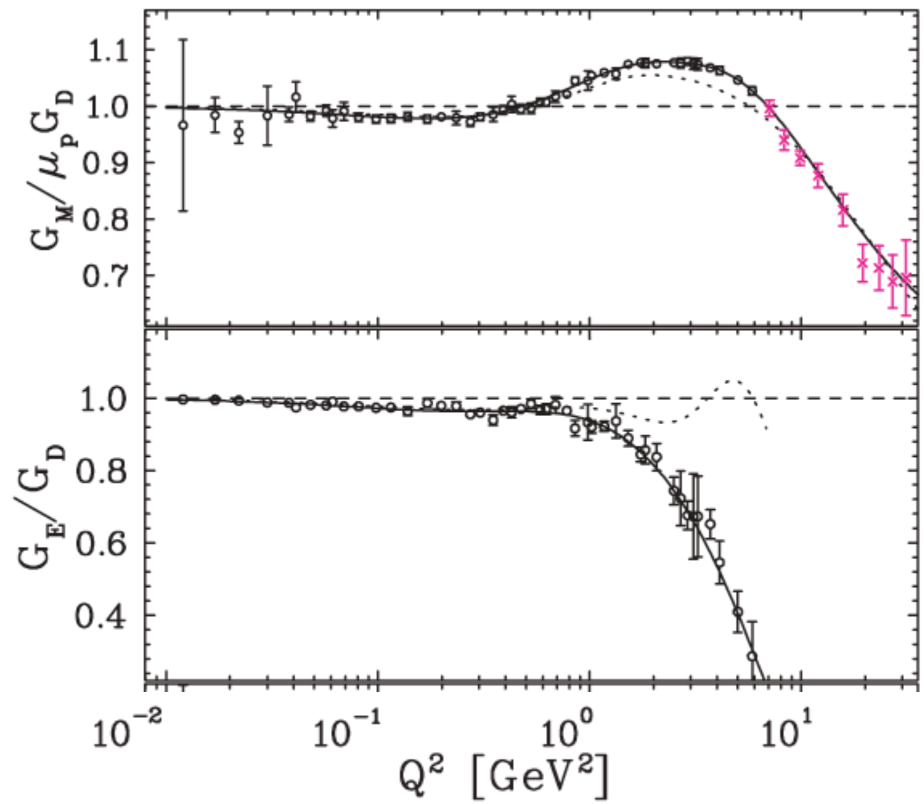


Plot courtesy B. Ziemer

A Short Diversion – the EM Form Factors

Measurements since 2000 of proton FF at JLab have shown significant deviations from dipole.

At low Q^2 deviation is small, but needs to be considered for G_A as precision increases at higher Q^2

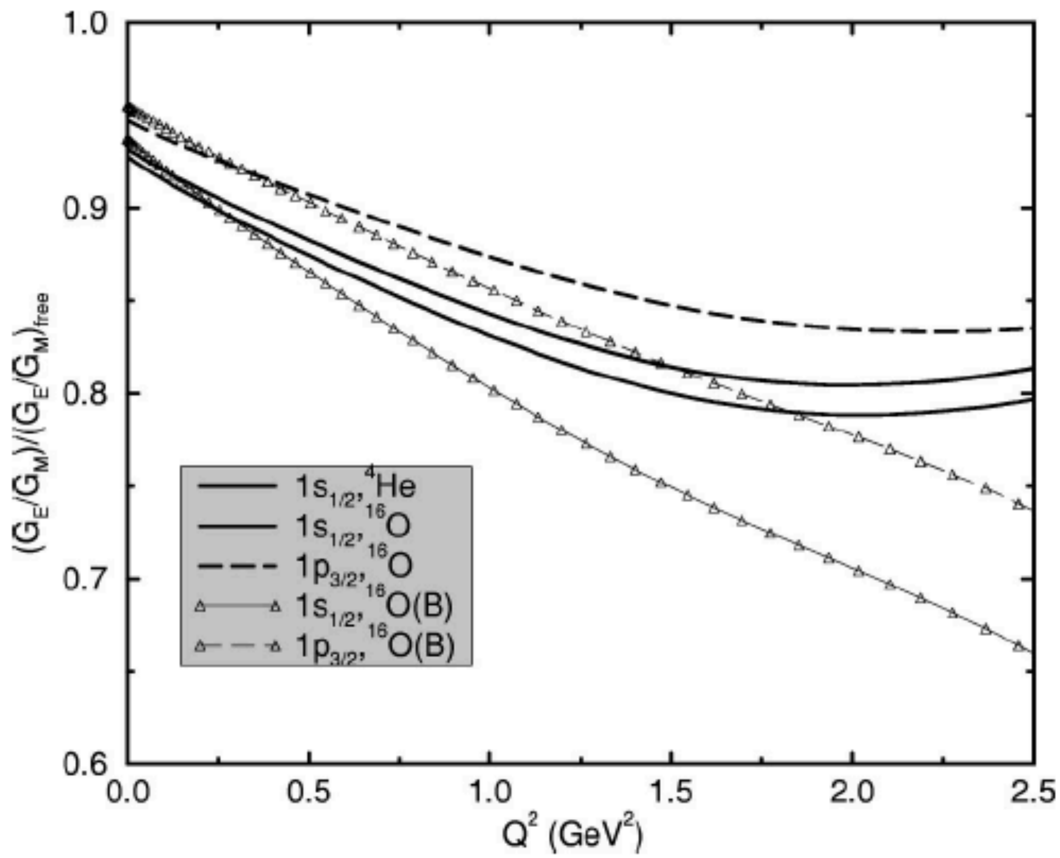


Plot from J. Arrington et al, PRC **76**, 035205 (2007)

Medium Modification of Form Factors

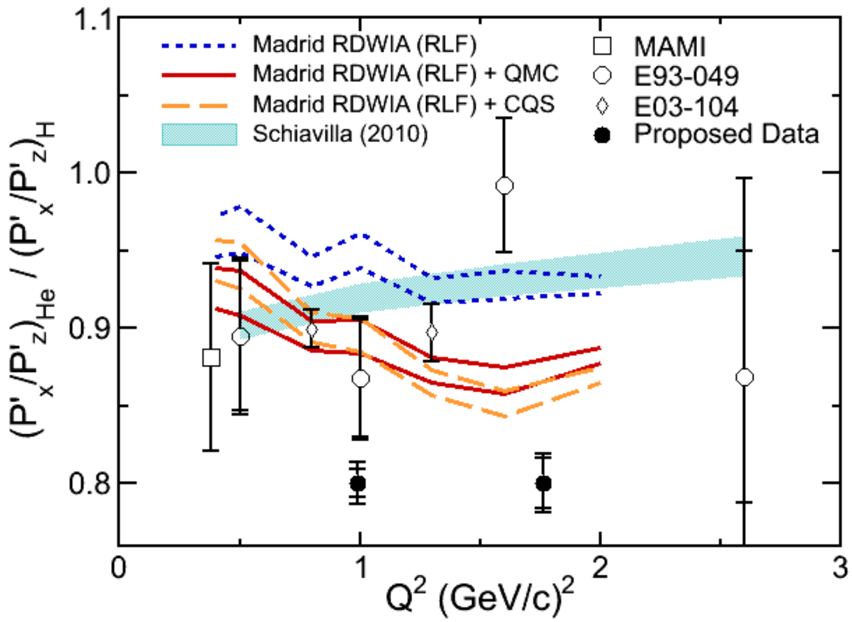
A. Thomas group has predicted modifications of EM FF at low Q^2

Ratio of G_E/G_M in ^{4}He 5-15% less than for free proton



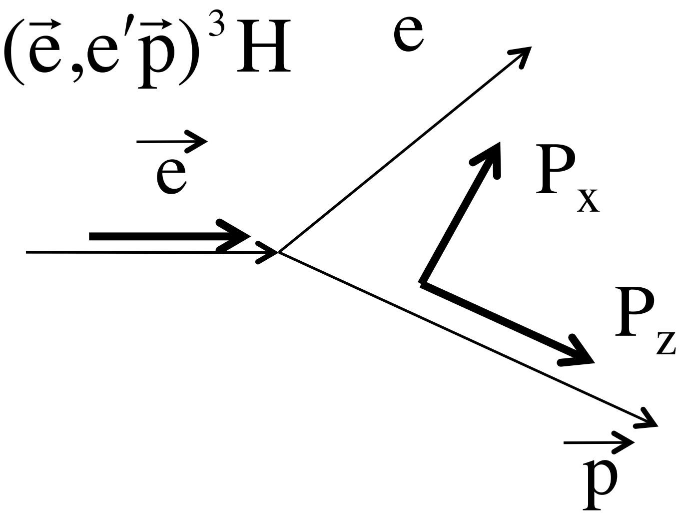
Lu et al., PRC **60**, 068201 (1999)

Measurements of polarization transfer on ^{4}He, which is sensitive to FF do not agree well with conventional models without FF modification



$$\frac{P_x}{P_z} \propto \frac{G_E}{G_M} \quad \text{for} \quad {}^{1}\mathrm{H}(\vec{e},e'\vec{p})\,{}^{1}\mathrm{H}$$

$${}^{4}\mathrm{He}(\vec{e},e'\vec{p})\,{}^{3}\mathrm{H}$$



M. Paolone et al, PRL **105**, 072001 (2010) and JLab proposal PR-11-002

Same model predicts G_A will decrease (opposite of what MiniBooNE sees)

Tsushima, Kim Saito PRC **70**, 038501 (2004)

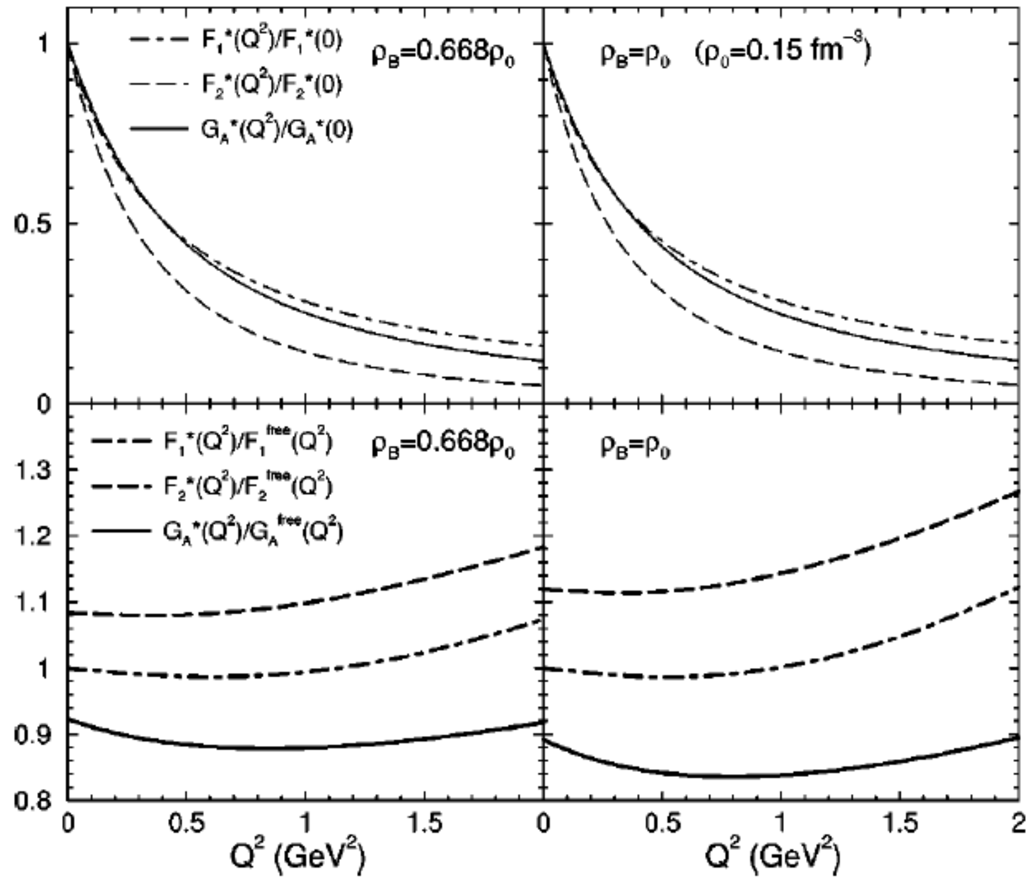
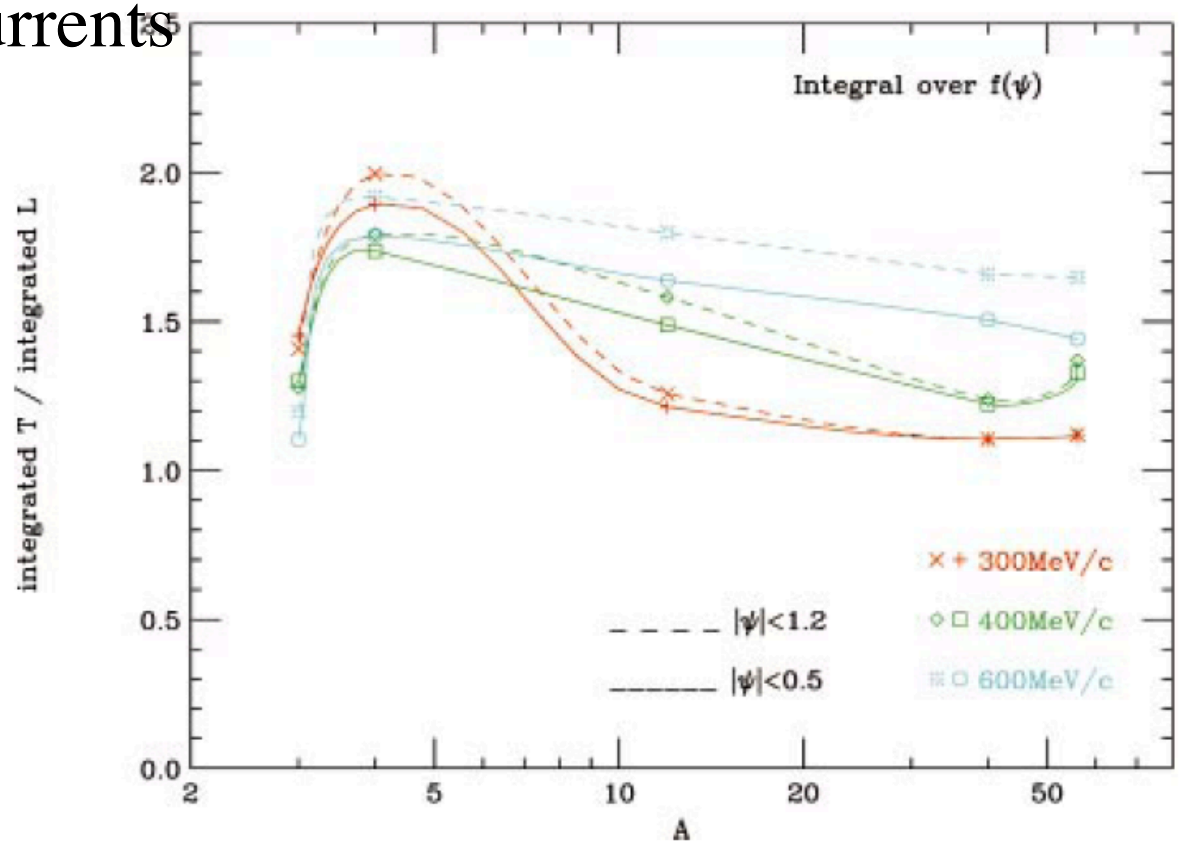


FIG. 1. Calculated ratios for the bound nucleon form factors.

More complications

Electron scattering from nuclei has shown a significant increase in the transverse response in electron scattering – attributed to short range correlations and meson exchange currents



Transverse response enhanced even in ^{4}He, with weak A dependence

Carlson et al., PRC **65**, 024002 (2002)

A Possible Solution

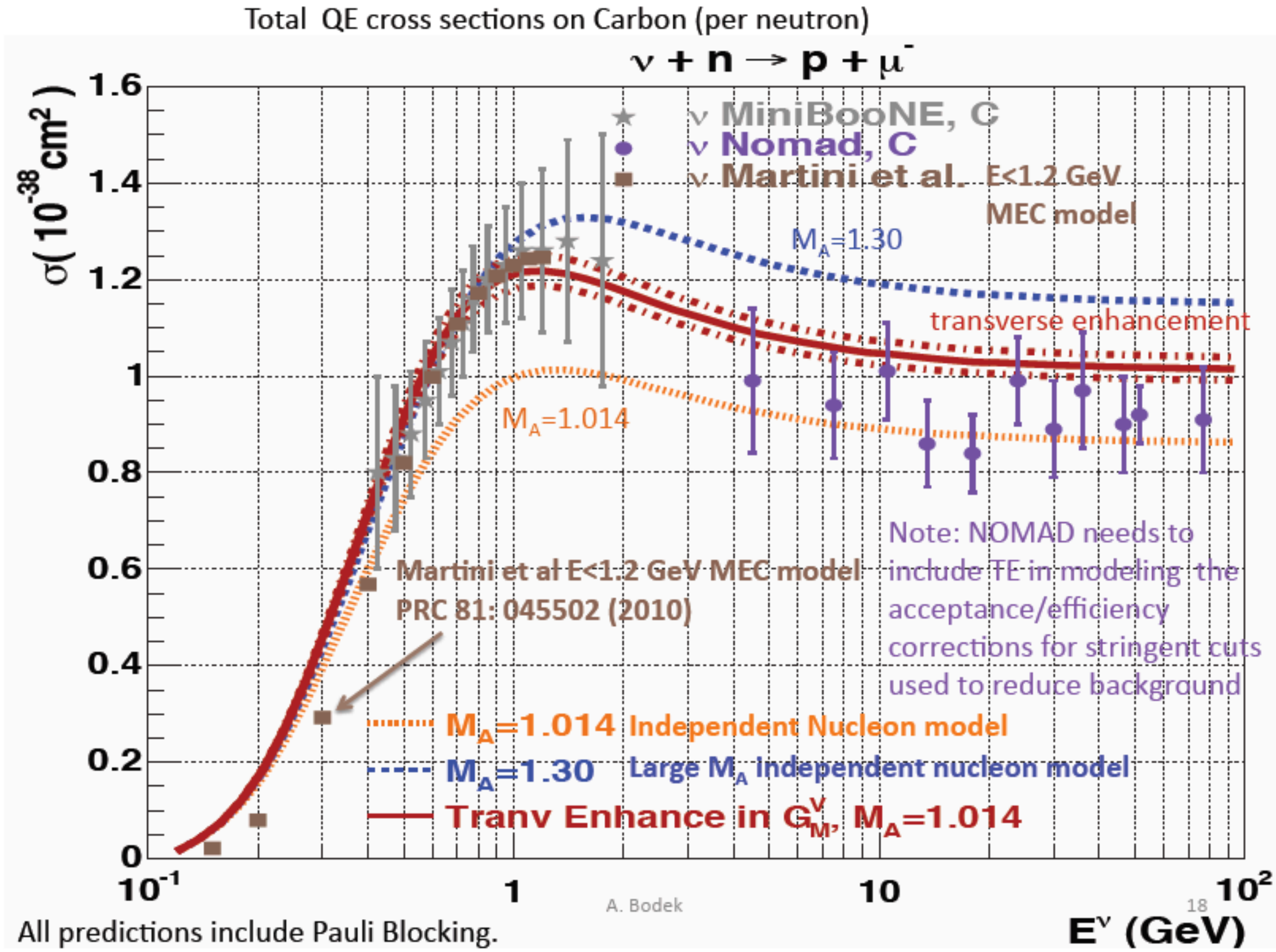
Extraction of G_A requires knowledge of the vector FF from EM scattering

Vector FF used are those from free nucleons

Nuclear effects may modify those FF or add additional effects mocking changes in those FF

A. Bodek et al. arXiv:1106.0340 [hep-ph] suggests modifying G_M to give agreement with the transverse enhancement brings MiniBooNE/Nomad into agreement

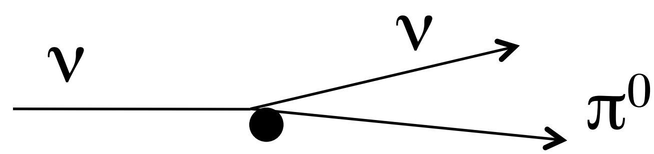
Bodek prediction fits without change in M_A



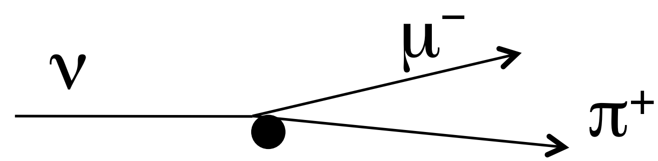
Coherent Pion Production

Coherent pion production occurs when the neutrino interacts with the entire nucleus, leaving it intact and producing a single pion.

$\nu A \rightarrow \nu A \pi^0$ NC production



$\nu A \rightarrow \mu^- A \pi^+$ CC production



It is a potentially significant background for oscillation experiments as well as interesting in its own right as a test of the neutrino-nucleus interaction

K2K/SciBooNE/MiniBooNE

MiniBooNE/SciBooNE – observed NC coherent π production at $E_\nu \sim 1$ GeV

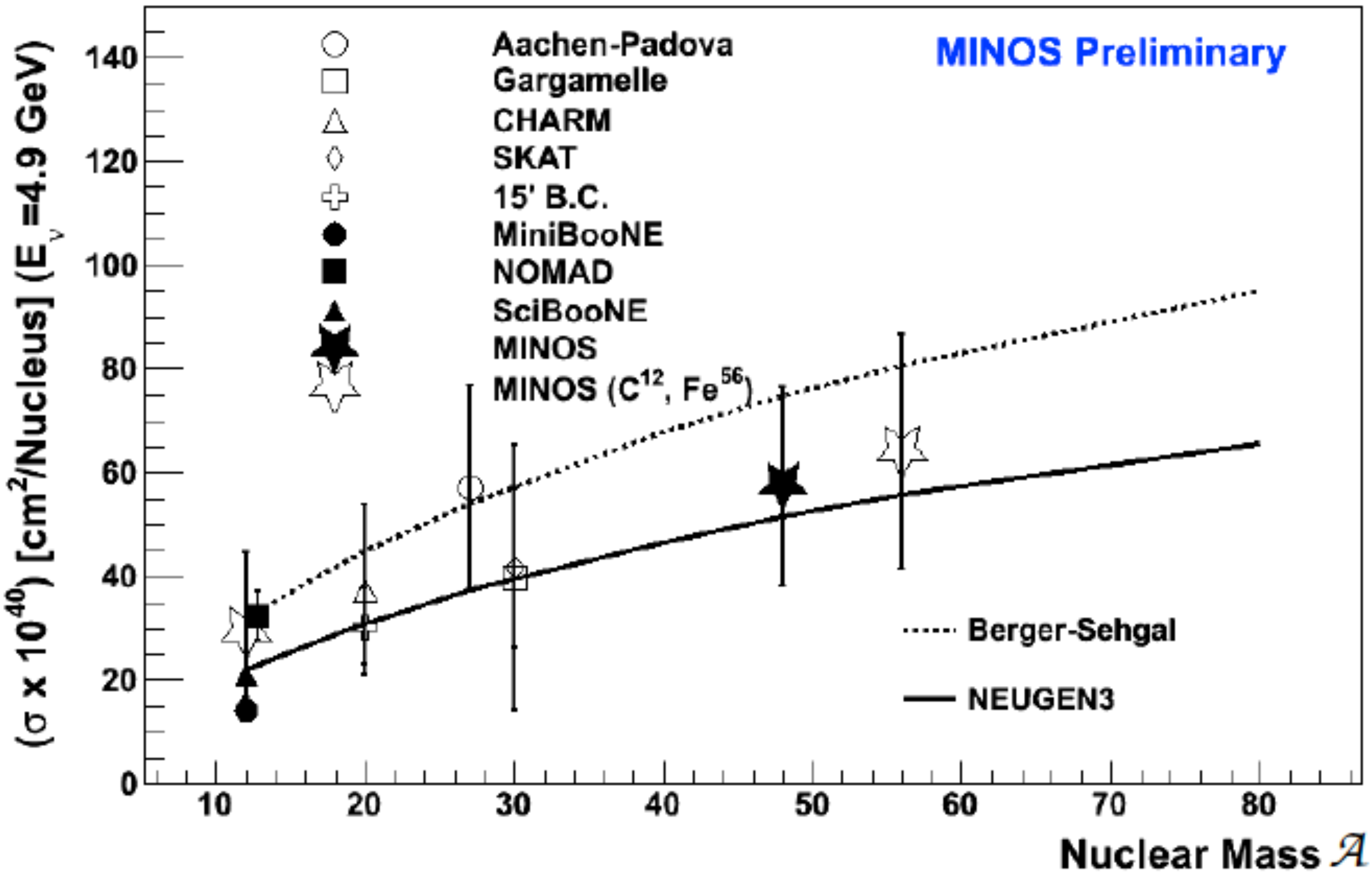
NC coh/CC total $(1.1 \pm 0.2) \times 10^{-2}$

In approximate agreement with Rein-Sehgal model

K2K/SciBooNE – no evidence for CC coherent π production

CC coh/NC coh < 0.1   Rein-Sehgal estimates about 1

MINOS results on C/Fe for NC coherent



D. Cherdack NuInt 11

A New Age of Neutrino Scattering

Data for neutrino scattering has sufficient statistical accuracy to challenge models of the interaction in nuclei!

New experiments are on the way which will continue this trend including MINERvA and T2K.

Prospects for MINERνA

Main INjector ExpeRiment ν−A

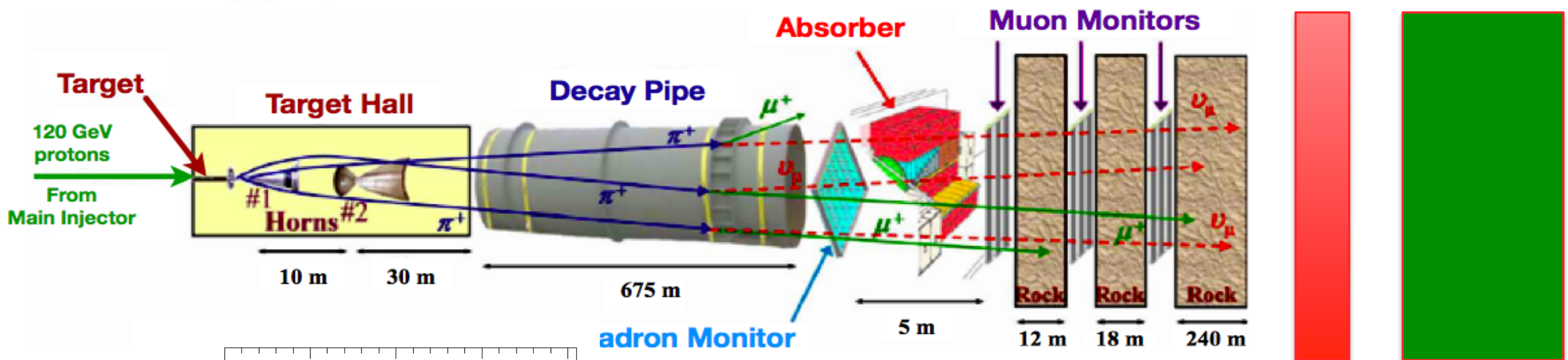
MINERνA is a high resolution neutrino cross section experiment in the NuMI beamline upstream of the MINOS near detector

Goal is to measure exclusive and inclusive neutrino cross sections in the energy range of 1-20 GeV with greatly improved precision, and on several nuclei

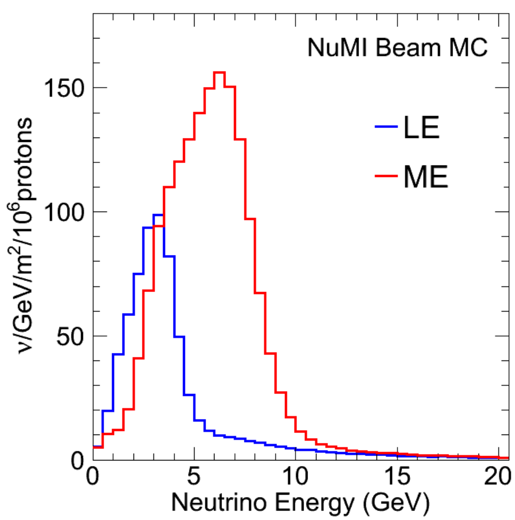
Collaboration between nuclear and particle physics communities (about 100 people)

The NuMI Beamline

MINOS



MINERνA

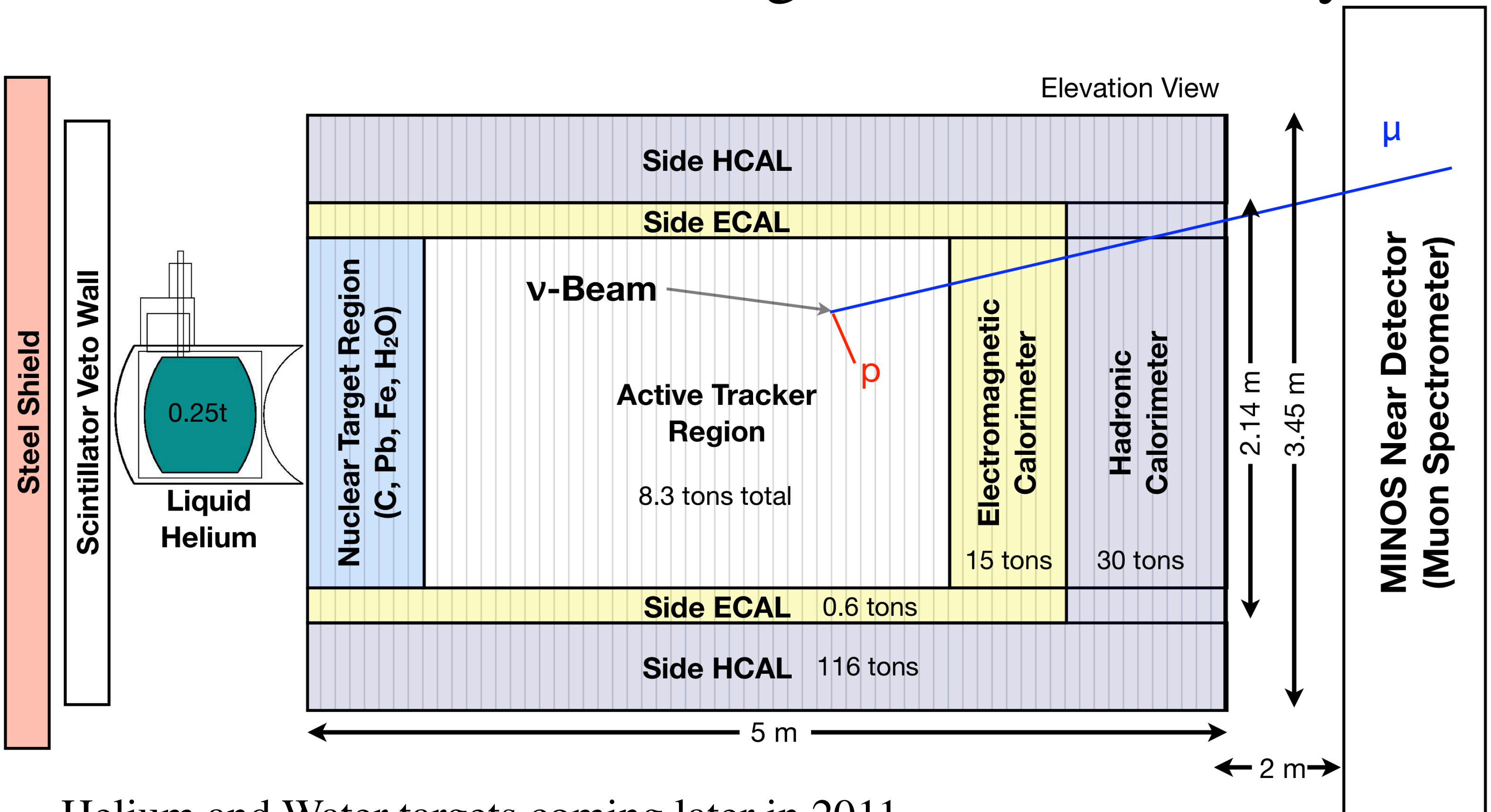


$$pC \rightarrow \pi^{+/-} \rightarrow \mu^{+/-}(\nu/\bar{\nu})$$

Spectrum can be changed by changing horn current or moving horns.

The Detector

120 modules of tracker, targets, and calorimetry



Helium and Water targets coming later in 2011

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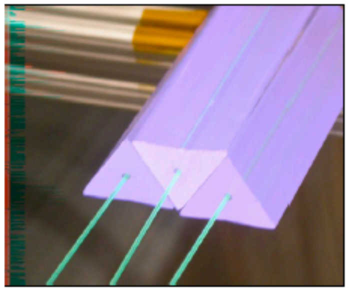
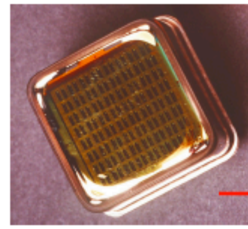
Tracking Detectors



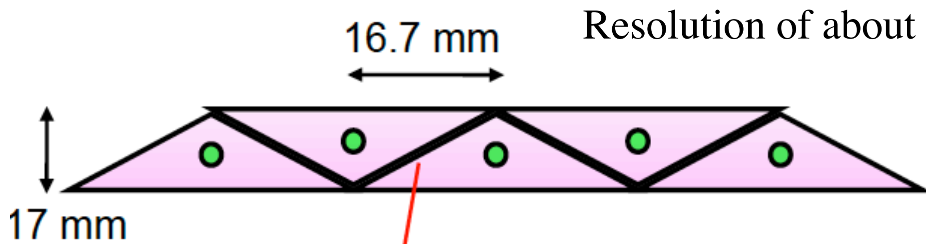
Extruded plastic scintillator
+ wavelength shifters.

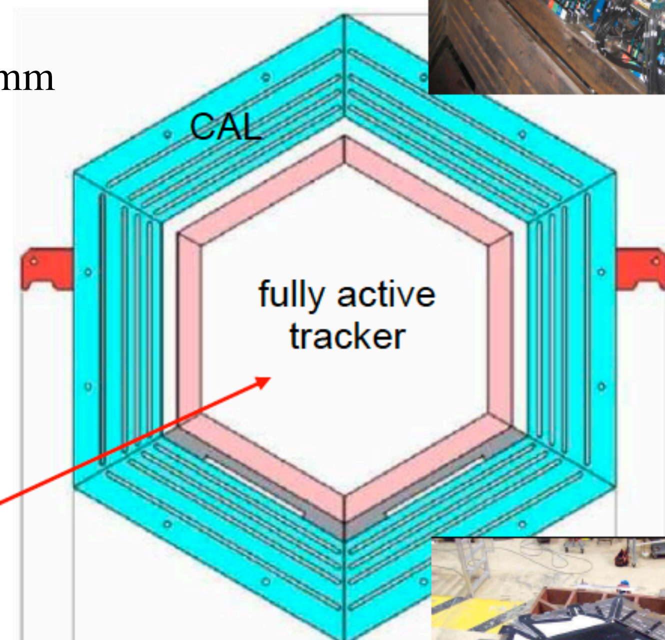
Triangular geometry allows charge sharing for better position resolution.

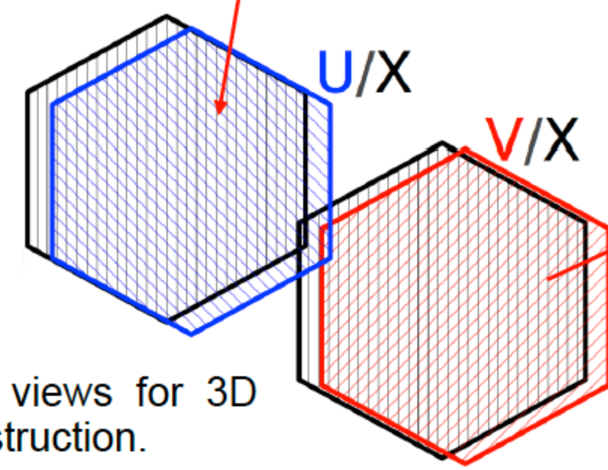


64 anode
PMT's

Resolution of about 3 mm

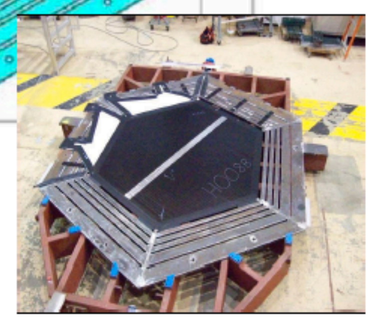






Three views for 3D reconstruction.

Iron outer detector instrumented for EM calorimetry.



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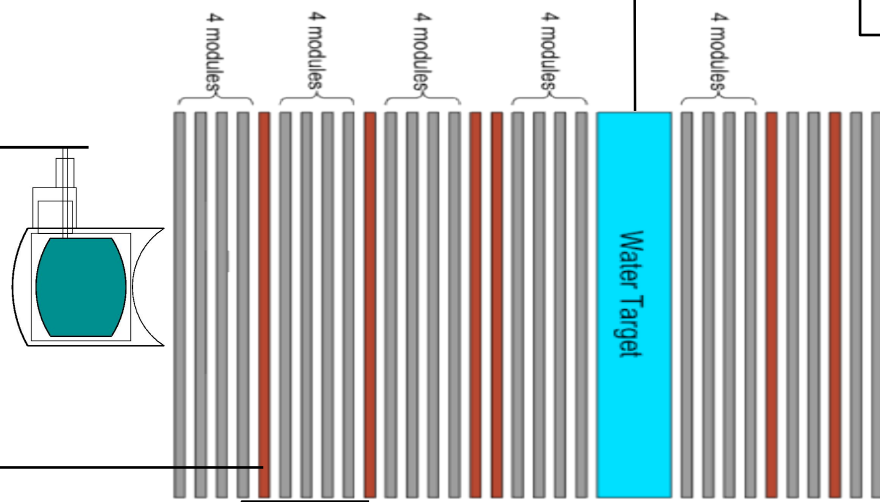
MINERνA Detector
Passive Targets

Liquid Helium

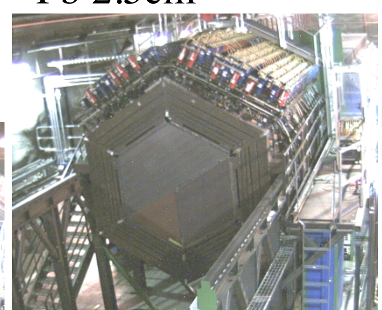


Water

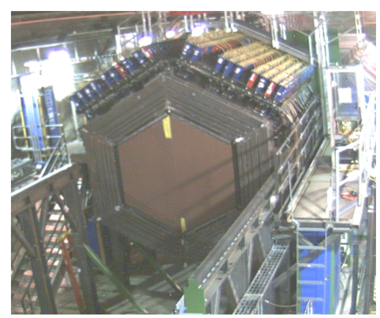
Fe 2.5 cm/Pb 2.5 cm

Fe 2.5 cm/Pb 2.5 cm

C 7.6 cm Fe 2.5 cm
Pb 2.5cm



Pb 0.8 cm



Fe 1.3 cm/Pb 1.3 cm

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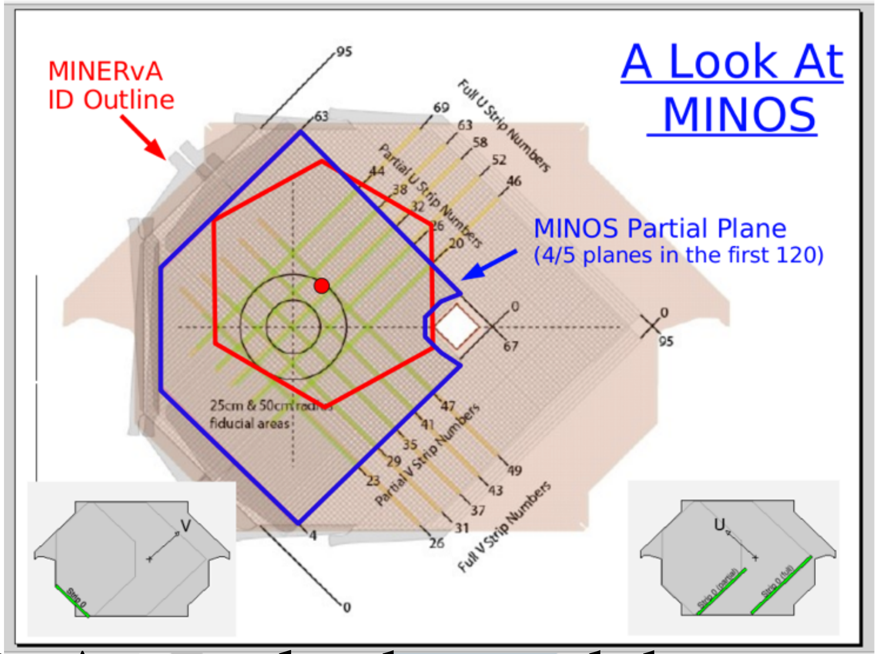
Muon Detection

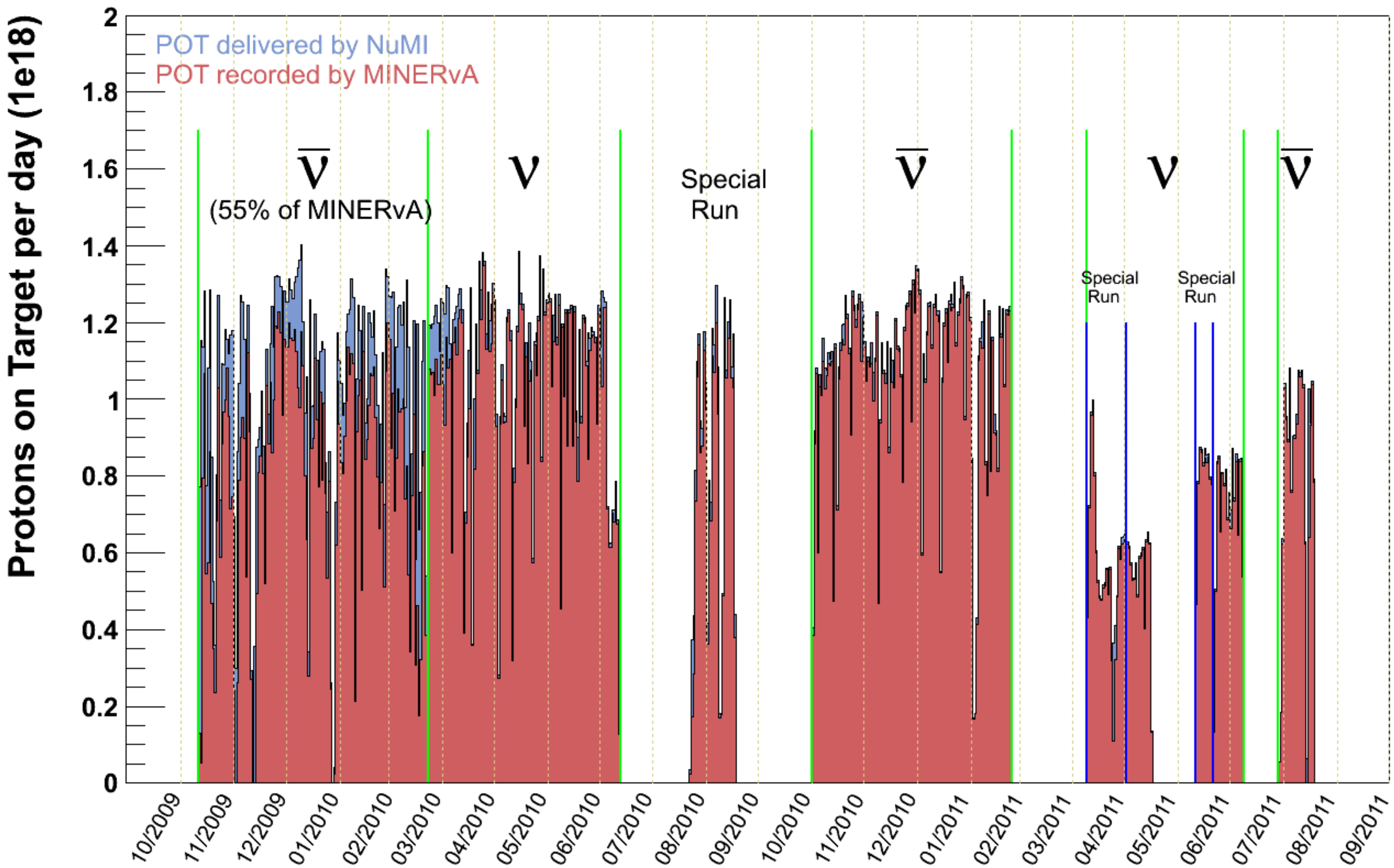
The MINOS near detector serves as a forward muon spectrometer.

Energy threshold ~2 GeV
Good angular acceptance up to scattering angles of about 10 degrees, with limit of about 20 degrees



Muons stopped in MINERνA can also be used, but no charge determination. Studies presented today use only events with muon in MINOS matched to muon in MINERνA

MINERνA has been running with high efficiency and collected data in both the neutrino and antineutrino mode



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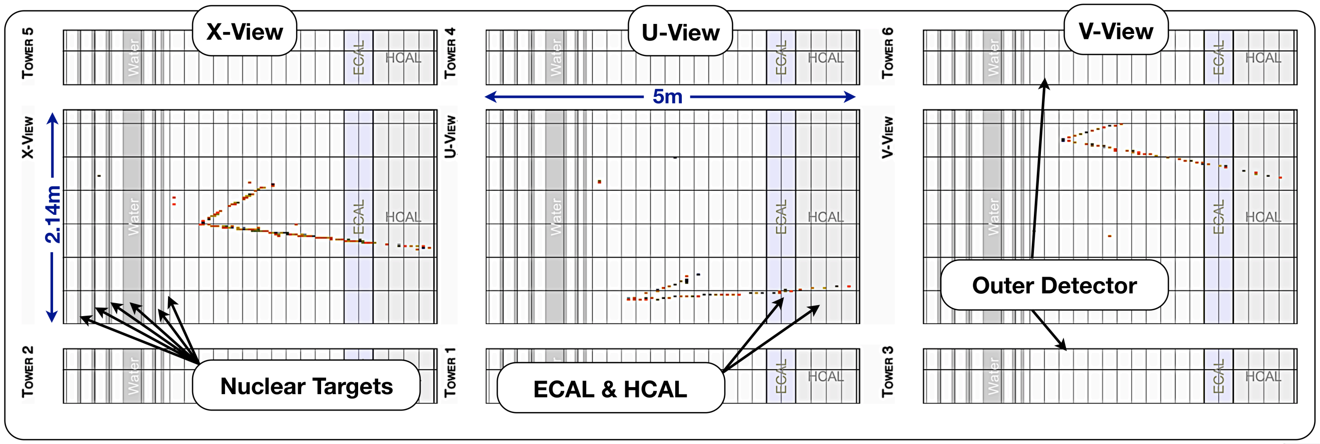
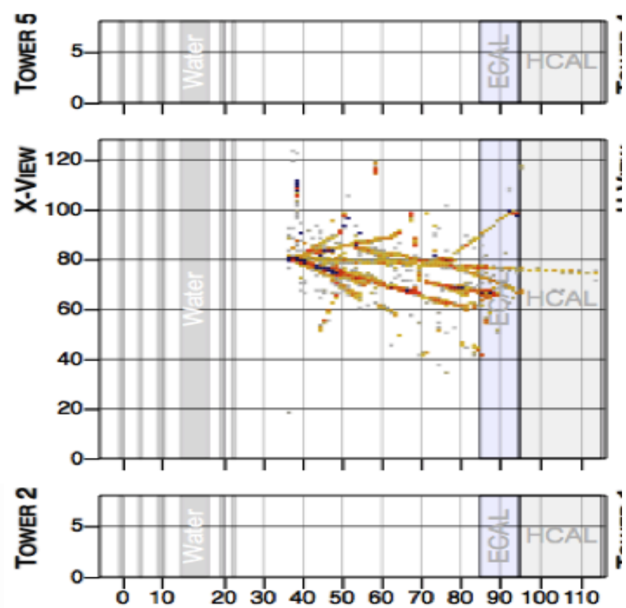
Sample events

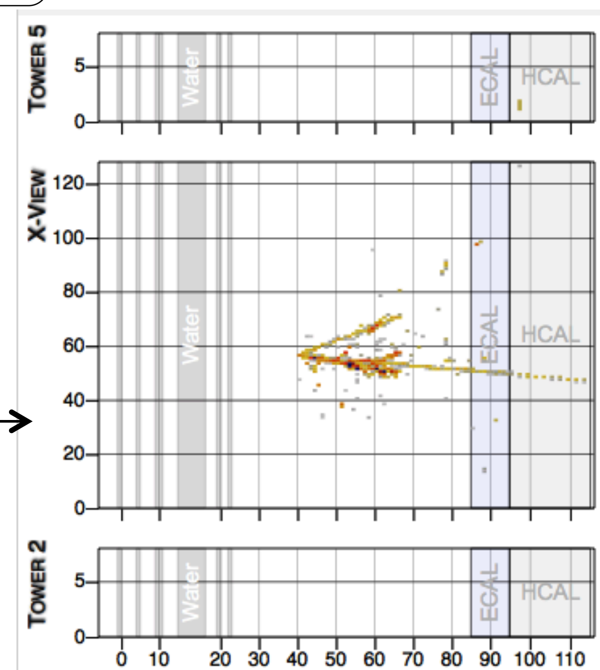


QE candidate

DIS candidate



Resonance candidate



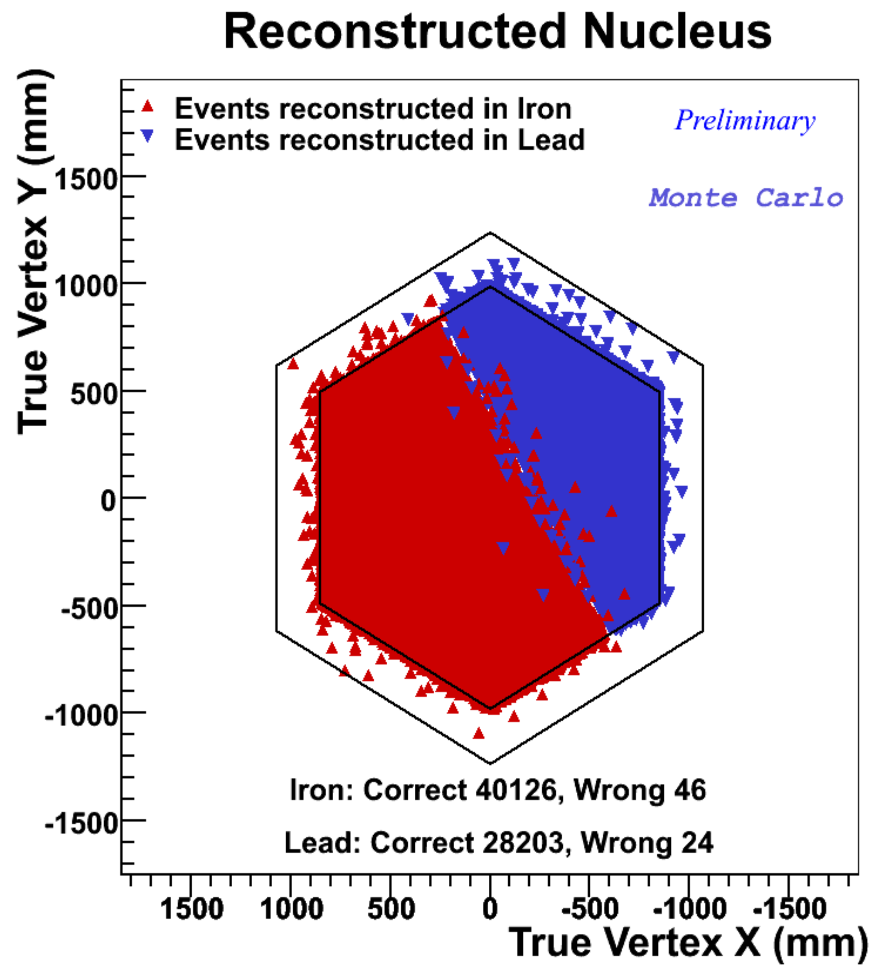
Inclusive ratio

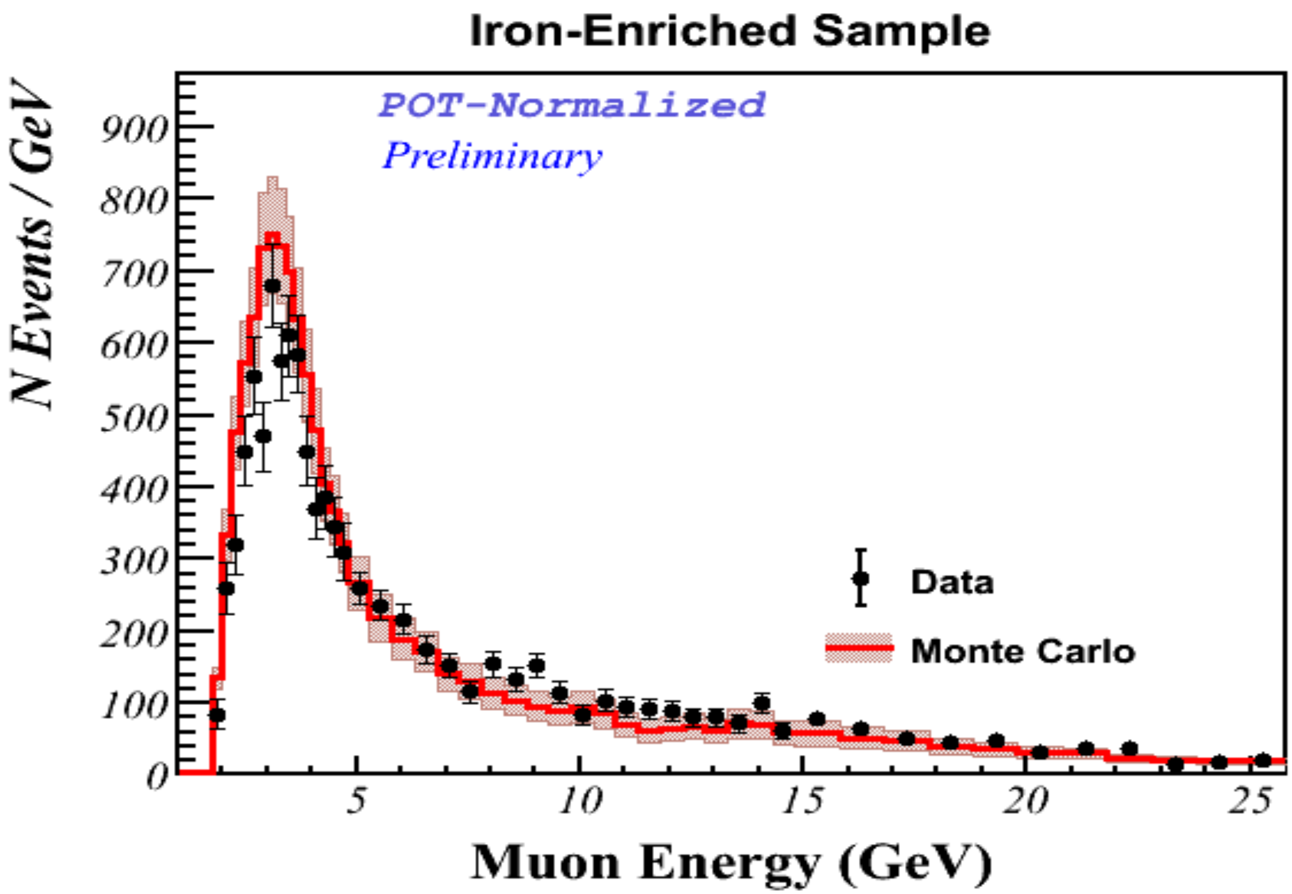
One of our first goals is to measure the inclusive cross section ratios of various nuclei.
Ratio depends both on the relative neutron to proton cross section, and possible nuclear modifications to the total cross section.

Analysis done with neutrino data, on most downstream Pb/Fe target

x-y tracking to plane is good, MC indicates that misidentification of target is a verv small effect.

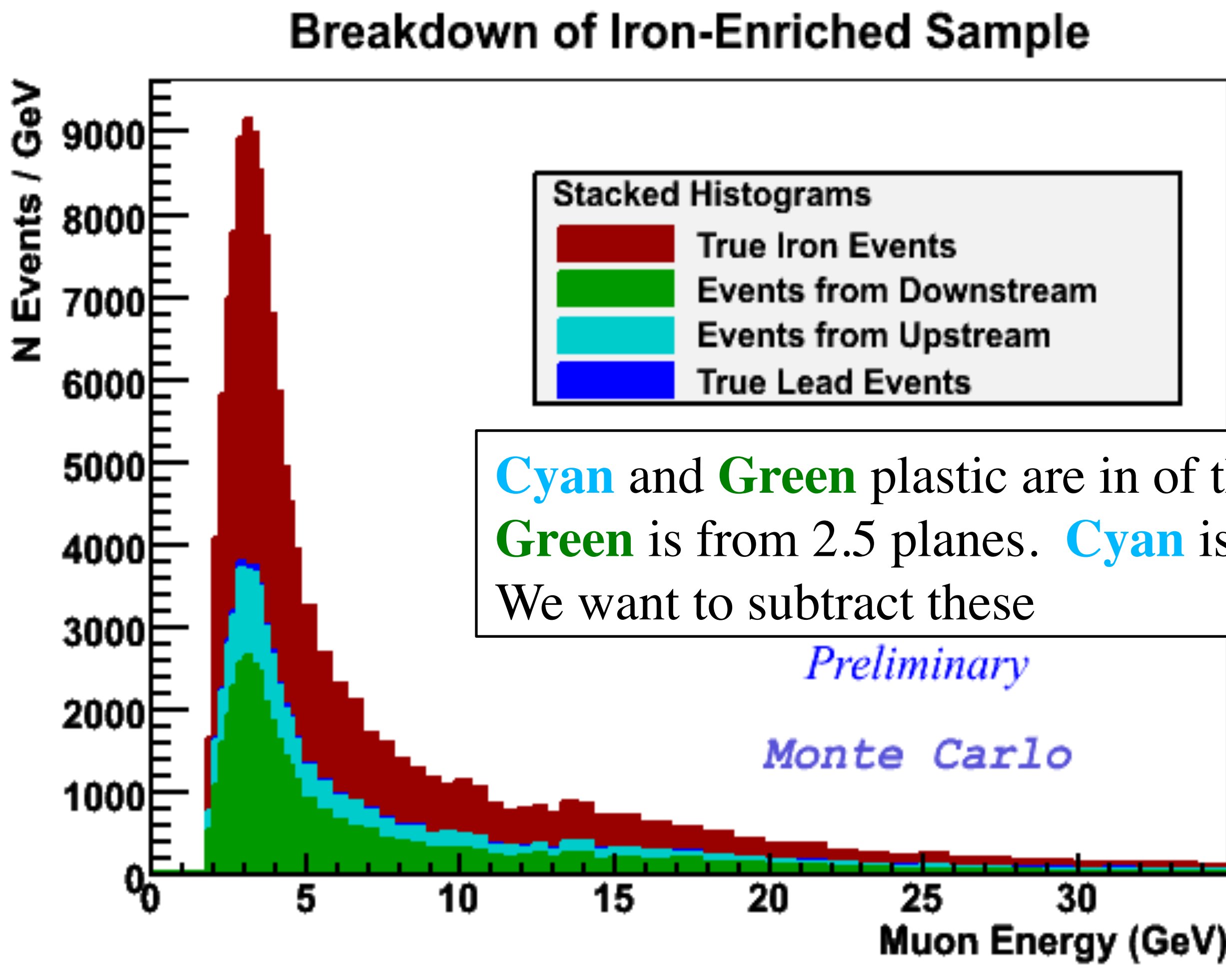
- **Blue** in **Red** area are selected as events from **Iron** but are truly events from **Lead**





1/20 of data 1/5 of mass and ¼ of exposure

Breakdown of events from “Fe” from MC



Cyan and Green plastic are in of the sample
Green is from 2.5 planes. Cyan is from 0.5 planes
We want to subtract these

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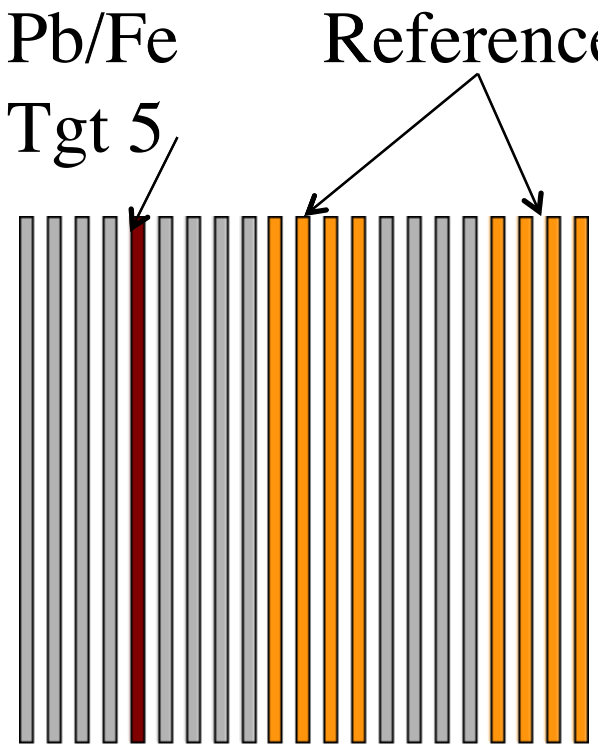
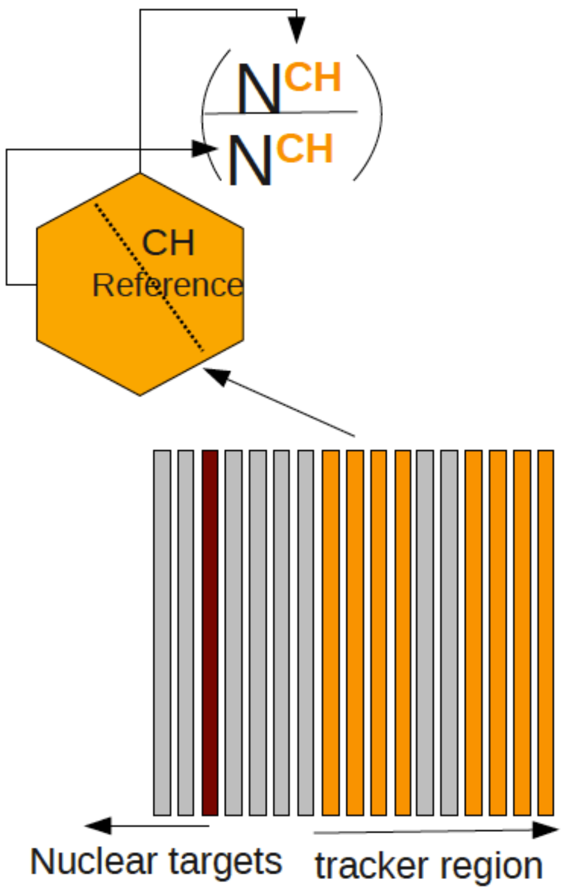
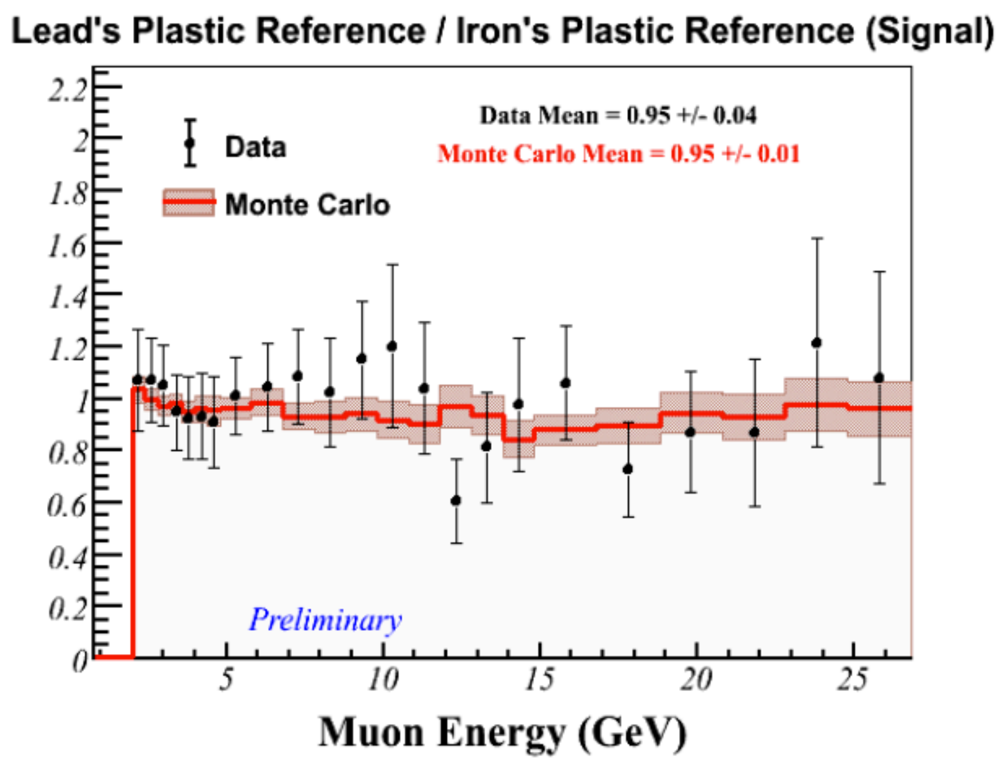
Making the Fe/Pb ratio also requires correcting for the acceptance difference for muons into MINOS, and subtracting the scintillator background



Making double ratio (Fe/CH)/(Pb/CH) of each nucleus to same area scintillator cancels (largely) acceptance difference

Ratio – Scint/Scint





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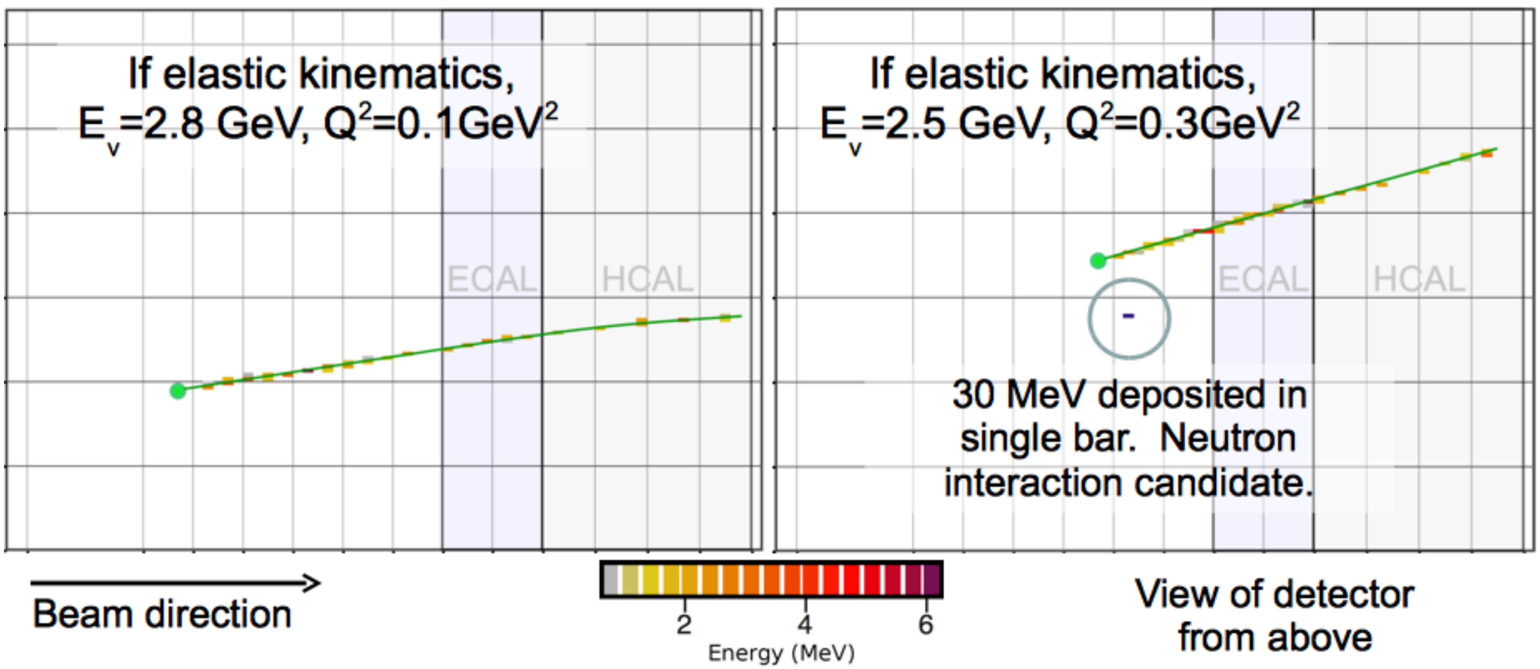
Anti-neutrino QE

Our other analysis which is most far along is study of anti-nu scattering in the tracking detector (i.e. CH) from the first running with the partial detector.

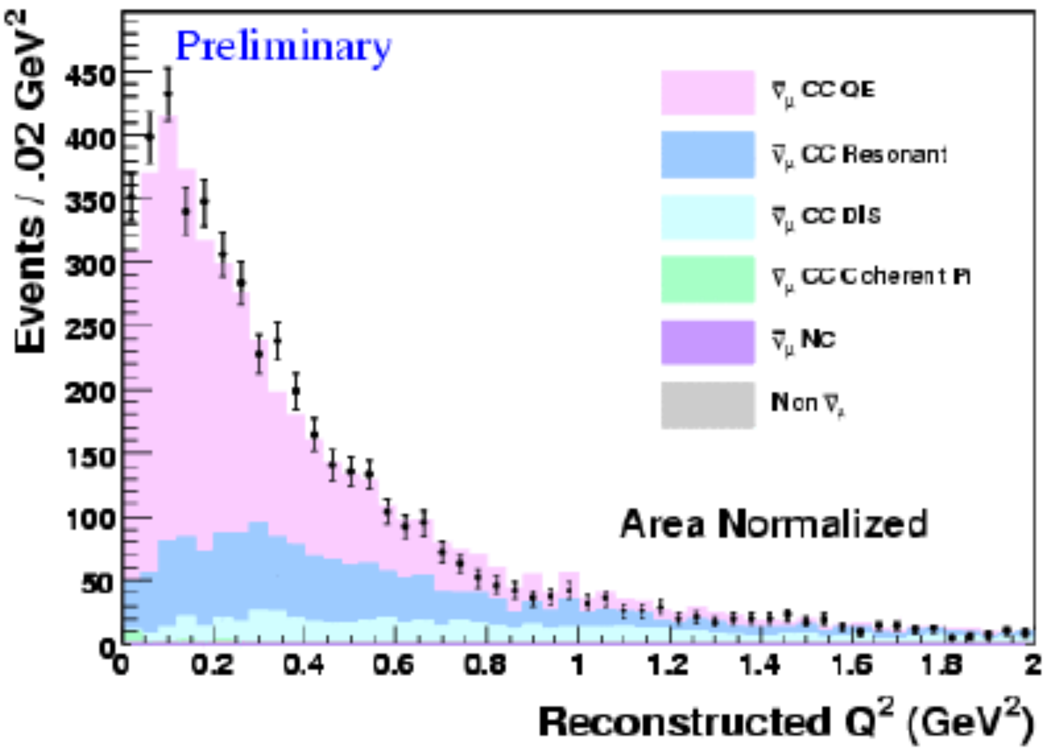
$$\bar{\nu} p \rightarrow \mu^{+} n$$

Characterized by single muon with little other observed energy

Anti-neutrino QE candidates



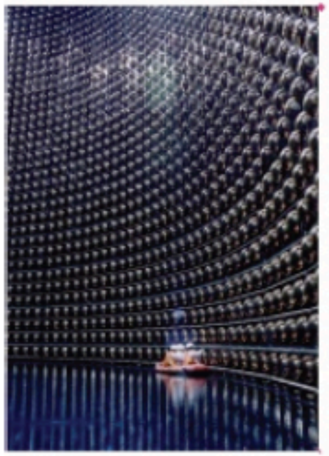
Area Normalized Q^2 Distribution



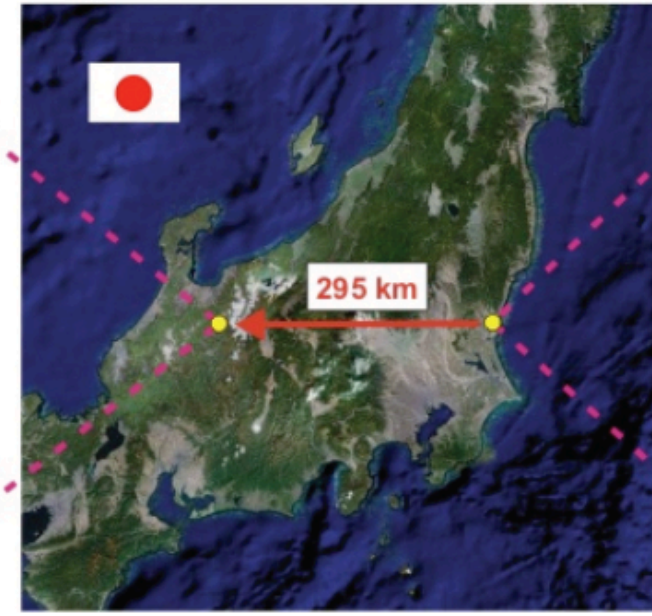
Only about 1/8 of anti-nu data, 1/30 of neutrino data!

T2K

Super Kamiokande
50,000 tons of water
10,000 phototubes

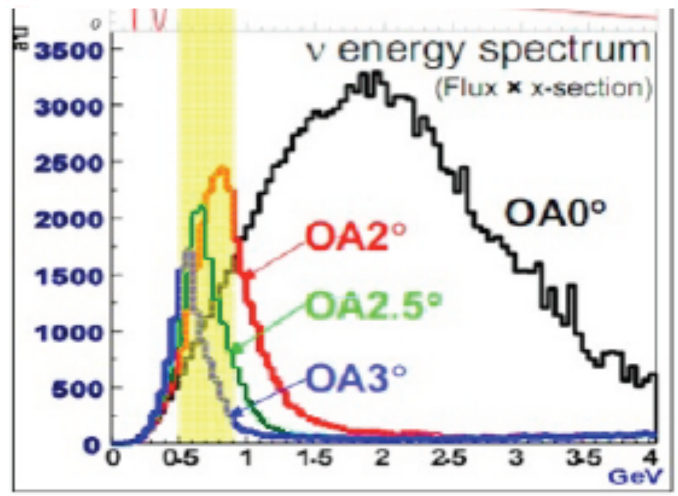


Neutrino beam directed across Japan



Tokai accelerator complex and
location of near detector (ND280)

- 295 km baseline
- 'Quasimonochromatic' beam
  -> first use of the off-axis technique
- Beam peak energy tuned to ~600 MeV, to give L/E at
  -> first maximum in ν_μ oscillation probability
  -> first maximum in ν_e appearance probability



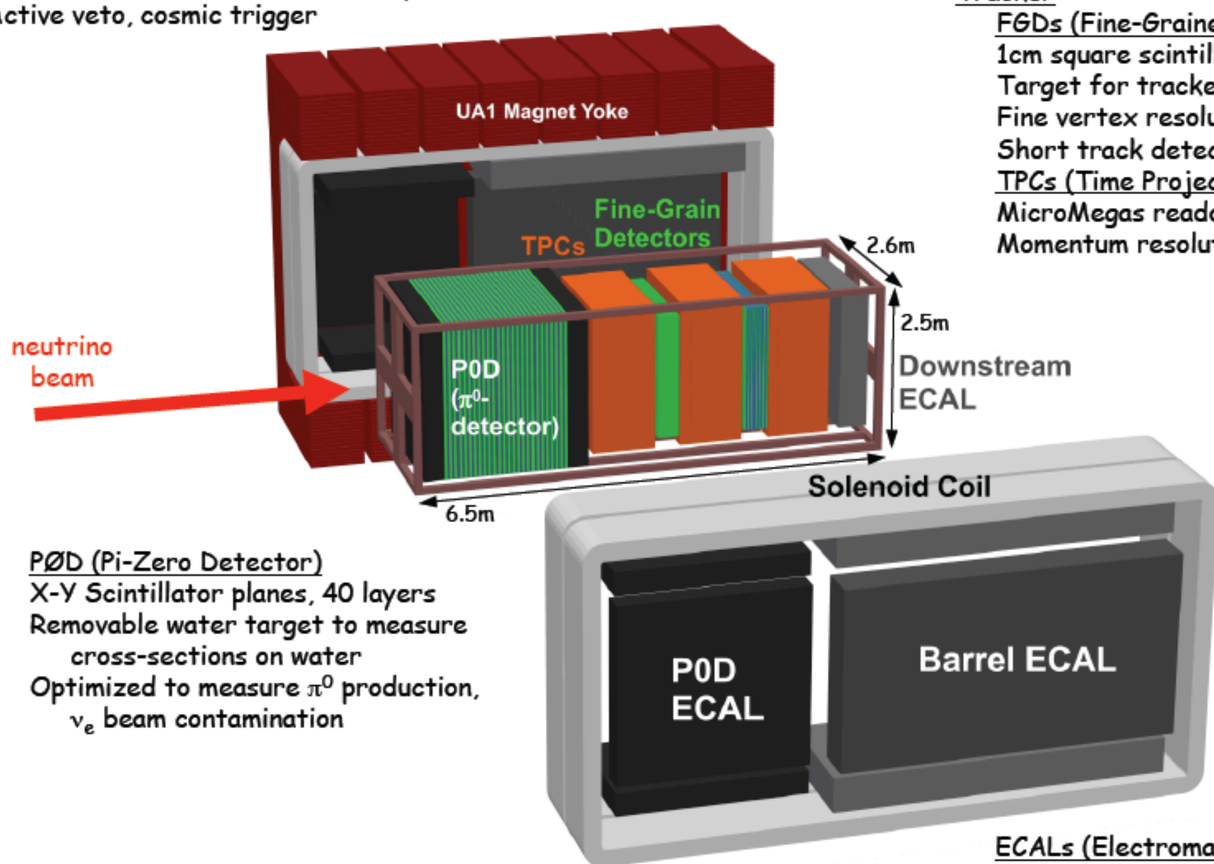
Thanks to B. Berger and T2K for slides

ND280 Off-Axis Detectors

SMRD (Side Muon Range Detector)
Scintillator interleaved in magnet yoke
Active veto, cosmic trigger

Magnet
UA1 magnet, B=0.2T nominal

Tracker
- **FGDs (Fine-Grained Detectors)**
  - 1cm square scintillator bars
  - Target for tracker
  - Fine vertex resolution
  - Short track detection: recoil protons
- **TPCs (Time Projection Chambers)**
  - MicroMegas readout (7mmx10mm pads)
  - Momentum resolution <10% @ 1GeV



PØD (Pi-Zero Detector)
X-Y Scintillator planes, 40 layers
Removable water target to measure cross-sections on water
Optimized to measure π^0 production, ν_e beam contamination

ECALs (Electromagnetic Calorimeter)
Scintillator + lead
Measure photons, electrons from tracker, PØD

ND280 Goals

Primary goals are driven by the oscillation analyses:

-> Characterize the neutrino beam:

- ν_μ measurement: beam flux*, muon momentum and angular distributions
  *(really the combination of flux and cross-section)
- ν_e measurement: intrinsic beam background

-> Cross-section measurements:

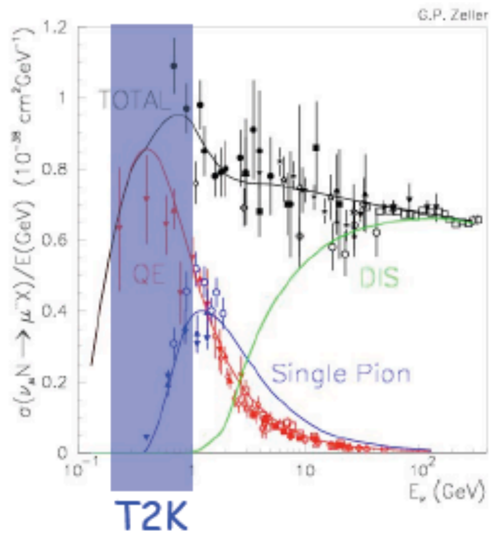
- $NC\pi^0$: important background to the ν_e appearance analysis
- Reduce cross-section uncertainties in the oscillation analyses

ND280 will also contribute to increasing understanding of neutrino cross-sections in their own right

-> High statistics

-> Unique beam and detector features:

- Quasimonochromatic beam at a lower energy than most previous measurements
- Measurements on specific targets
  - -> PØD water in/out
  - -> water/carbon via FGD precision vertexing
- photon reconstruction
- recoil proton tracks in FGD



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Summary

- An exciting period for neutrino interaction measurements
- QE studies will give much improved measurement of axial form factor
  - Need to understand nuclear effects
- Coherent pion production surprises
- New high statistics, good resolution results on the way